

# The NASA Astrophysics Data System: Sociology, Bibliometrics, and Impact

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## ABSTRACT

The NASA Astrophysics Data System (ADS), along with astronomy's journals and data centers, has developed a distributed on-line digital library which has become the dominant means by which astronomers search, access and read their technical literature. By combining data from the text, citation, and reference databases with data from the ADS readership logs we have been able to create Second Order Bibliometric Operators, a customizable class of collaborative filters which permits substantially improved accuracy in literature queries. Using the ADS usage logs along with membership statistics from the International Astronomical Union and data on the population and gross domestic product (GDP) we develop an accurate model for world-wide basic research where the number of scientists in a country is proportional to the GDP of that country, and the amount of basic research done by a country is proportional to the number of scientists in that country times that country's per capita GDP.

We examine the obsolescence function as measured by actual reads, and show that it can be well fit by the sum of four exponentials with very different time constants. We compare the obsolescence function as measured by readership with the obsolescence function as measured by citations. We find that the citation function is proportional to the sum of two of the components of the readership function. This proves that the normative theory of citation is true in the mean. We further examine in detail the similarities and differences between the citation rate, the readership rate and the total citations for individual articles, and discuss some of the causes.

Using the number of reads as a bibliometric measure for individuals, we introduce the read-cite diagram to provide a two-dimensional view of an individual's scientific productivity. We develop a simple model to account for an individual's reads and cites and use it to show that the position of a person in the read-cite diagram is a function of age, innate productivity, and work history. We show the age biases of both reads and cites, and develop two new bibliometric measures which have substantially less age bias than citations: SumProd, a weighted sum of total citations and the readership rate, intended to show the total productivity of an individual; and Read10, the readership rate for papers published in the last ten years, intended to show an individual's current productivity. We also discuss the effect of normalization (dividing by the number of authors on a paper) on these statistics.

We apply SumProd and Read10 using new, non-parametric techniques to rank and compare different astronomical research organizations. We then introduce the concept of utility time to measure the impact of the ADS and the electronic astronomical library on astronomical research. We find that in 2002 it amounted to the equivalent of 736 FTE researchers, or \$250 Million, or the astronomical research done in France.

*Subject headings:* digital libraries; bibliometrics; sociology of science; information retrieval

## 1. Introduction

The NASA Astrophysics Data System Abstract Service resides at the center of the most sophisticated discipline centered bibliographic system ever developed (Boyce 1998), (Boyce 1996). The typical astronomer, on average, uses the ADS every day; ADS users read approximately five to ten times the number of papers which are read in all the (traditional) astronomy libraries of the world, combined.

A detailed technical and historical description of the ADS can be found in a set of four papers: Kurtz et al. (2000), Eichhorn et al. (2000), Accomazzi et al. (2000), and Grant et al. (2000).

The key fact which links the sections of this paper together is that the existence of digital libraries, like the ADS, means that detailed information on the readership of journal articles, on a per article and per reader basis, can now be routinely obtained. This is basically a new bibliometric measure of importance equal to citations.

In section 2 we briefly describe the system, and note some of its more important or sophisticated features. In section 3 we describe the growth and current use of the system, and in section 4 we use ADS usage to show the relationship a country's wealth and population has with the number and effectiveness of its scientists.

In section 5 we develop a four component model to describe how the astronomy literature becomes obsolete (as measured by actual article reads) with age, and in section 6 we demonstrate the close connection between citations and readership.

In section 7 we develop a methodology to evaluate the research performance of individuals, using a combination of citations and readership, and we look at several interesting cases. Extending the results for individuals in section 8, we then develop techniques for comparing organizations.

Finally in section 9 we discuss how the total impact of the ADS and the electronic astronomy library can be evaluated; and we conclude in section 10 by discussing some of the future consequences of the new technologies and data used here.

## 2. Descriptive Background

The ADS Abstract Service was first demonstrated in 1992 (Kurtz et al. 1993) and was put

on-line for general use in April 1993. In early 1994 the service was moved onto the World Wide Web from its original NASA developed network home (Murray et al. 1992). In this section we will briefly describe some of the more important milestones and features in the ADS development; Kurtz et al. (2000) contains a detailed description of the early history of the ADS Abstract Service.

The ADS from the beginning has been designed to be used primarily by end-user astronomers, as opposed to librarians. This has led us to create a system which emphasizes recall over precision, assuming that the expert user can easily separate the desired from the undesired. The behavior of the system can be easily modified from its default, however, to match almost any desired searching style.

From the beginning our standard search involved partial match techniques, natural language queries with an extensive discipline specific synonym list, relevance feedback, and the combination of evidence (Belkin, et al. 1995) from simultaneous queries, such as text from the abstract combined with text from the title, combined with an author's name.

Within a few months of the initial public release, in 1993, we were able to include the ability to query for papers containing information about a particular astronomical object (i.e. a particular star or galaxy) by performing simultaneous joint queries with the SIMBAD data base (Wenger et al. 2000), operated by the CDS (Centre des donnees astronomique de Strasbourg) in France. We believe this is the first time the internet was used to permit routine joint transatlantic queries of this sort.

Also, soon after moving to a web based system, we were able to make direct hyperlinks between the bibliographic entries and on-line versions of data tables from those articles from the journal *Astronomy & Astrophysics* kept by the CDS in Strasbourg (Ochsenbein and Lequeux 1995). This capacity has grown so that now essentially every data table from every article in every major journal of astronomy is available via these means.

Towards the end of 1994, the ADS began scanning (creating bi-tonal bitmapped images of) recent issues of *The Astrophysical Journal (Letters)*. With the collaboration of virtually every astron-

omy journal we now have electronic copies of nearly every astronomy research paper published in the last fifty years, and with the collaboration of the Center for Astrophysics' Wolbach Library and the Harvard University Library (Corbin and Coletti 1995) we expect in the near future to have a nearly complete collection of the astronomy research literature going back two centuries. This collection has been called "Earth's Largest Free Full-Text Science Archive" (Highwire 2001).

In July 1995, *The Astrophysical Journal (Letters)* published its first issue in HTML electronic format (Boyce 1995), (Dalterio et al. 1995); it was the first major scientific journal to be fully on-line. The reference sections of that first electronic issue had hyperlinks from the references to the corresponding entries in the ADS. This practice of linking from the electronic article references to the relevant sections of a bibliographic service has now become standard for electronic journals; now all astronomy journals, and several others, link to the ADS.

Also in 1995 the ADS made its first links between a bibliographic reference and the data which were used to do the research described in the article (Plante et al. 1996). This practice has grown tremendously; more than 175,000 such links are now in the ADS, and the growth is becoming more rapid as part of the emerging Astronomical Virtual Observatory (Brunner et al. 2001), (Kurtz and Eichhorn 2001).

In 1996, using data purchased from the Institute for Scientific Information (ISI) with funds provided by the American Astronomical Society (AAS) as part of the electronic *Astrophysical Journal* project, we provided links from the main article references to lists of the papers they referenced, and to the papers which cite them (Kurtz et al. 1996). With the cooperation of all the main journals of astronomy we have since greatly expanded this capability, by purchasing more data from ISI, by performing optical character recognition on the reference sections of scanned articles in our database, and by taking directly the references from electronic articles provided to us by the publishers (Demleitner et al. 1999). Currently there are more than 8,000,000 citing-cited article pairs in our database, and the number continues to grow.

In 1996, we began maintaining mirror sites

around the world (Eichhorn et al. 1996); the first was hosted by the CDS in Strasbourg. Currently we have twelve mirrors in twelve countries on four continents.

In 2000, we added the ability to see articles which were the most read by people who read another article (i.e. people who read this article also read: . . . , hereafter also-read). Because ADS users read a substantial fraction of all astronomy articles (see sections 3 and 9) this feature provides an accurate sampling of the entire discipline.

## 2.1. Second Order Operators

In 1997, we began permitting some second order queries (Kurtz 1992) by allowing the result of a query to be the collated reference or citation lists of the articles returned by the query, rather than the articles themselves (Kurtz et al. 2000). In 2001 we added the also-read lists to this capability, and created a new interface, both to make it more intuitive, and to improve its functionality. The resulting set of second order operators provides an extremely powerful basis for creating specialized collaborative filters (e.g. Goldberg, et al. (1992)). We believe many of these capabilities are unique to the ADS.

A full description of the second order operators will be published elsewhere (Kurtz et al. 2002); here we will give one example of their use, in order to demonstrate their power.

We will begin by assuming that we are interested in the current state of knowledge in subfield X. We will further assume that we know enough about subfield X (by knowing an author's name, perhaps) to be able to find the abstract of at least one paper about subfield X.

We retrieve the abstract(s) using the ADS and use the "find similar abstracts" feature, modifying the query to return only articles published within the past year, we then retrieve a list of the recent papers with the most similar abstracts. This is a list of the most recent papers in subfield X based on similarity of text. We can now use the second order operators.

The people who have recently read the most recent papers on subfield X are people who are interested in subfield X; the papers they read the most will be the currently most popular papers on subfield X. Clicking on the "get also-read lists"

feature retrieves exactly those most popular articles on subfield X.

These papers are the most popular for a reason; presumably they are informative papers concerning the current state of affairs of subfield X. The papers most referenced by these papers would be those currently most useful to subfield X; clicking on the “get reference lists” feature gets this list of most useful (most cited by papers in subfield X) articles.

Papers which cite a large number of these most useful articles are papers with extensive discussions of topics of interest to subfield X; they are the most instructive articles about subfield X. Clicking on the “get citation lists” feature gets this list of most instructive articles. Figure 1 shows this list after following the above procedure starting with the abstract from the paper by Riess et al. (1998) “Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant.” The score refers to the number of references in the previous list which are also cited by these articles. For example, the top article in this list cited 96 of the papers from the previous list of most referenced papers; for three of the five papers shown more than half of all the papers in their reference lists were also in the previous list. All of the articles on the top of the list are review articles on exactly the original subject; the high quality of this list tends to validate each stage of the process.

Beginning with a minimum of knowledge (the ability to find a single article on the desired subject) we are quickly able to obtain lists of the most current, most popular, most useful, and most instructive articles about the desired subject. Given the ability to write a good query, or to edit the lists to include only the most relevant articles, one can obtain in-depth results for very narrow subject matters. Of course very many different ways of using these second order operators are possible.

While we believe our use of these second order operators is unique, there are some similar features in other systems. The “customers who bought this book also bought” feature of Amazon.com (Amazon 2002) and other on-line retailers is similar to using the “get also-read” feature on a single article. The “get related records” feature of ISI’s Web of Science (ISI 2002) is the same as running the “get citation lists” feature on the reference list from a single article.



Fig. 1.— The “most instructive” papers list obtained by following the procedure described in the text, beginning with the abstract from Riess et al. (1998).

### 3. The Growth of the ADS

The ADS went on-line in April 1993 using a wide area networking system created for NASA; in its ten months of existence usage approximately doubled. In February 1994, the ADS converted to the World Wide Web (Grant et al. 1994); usage went up by a factor of four within five weeks. Since then use of the ADS has doubled about every two years. There are a number of different ways to measure ADS use, figure 2 shows the number of unique users per month. The dotted line shows a two-year doubling.

We caution that the number of unique users may be misleading. We track usage by the number of unique “cookies”<sup>1</sup> which access the ADS, and by the number of unique IP<sup>2</sup> addresses. This leads to a number of unique users which may ex-

<sup>1</sup>A cookie is a unique identifier which WWW providers (in this case ADS) assign to each user, and store on the user’s computer using the browser.

<sup>2</sup>Each Machine on the internet has a unique IP (Internet Protocol) address.

TABLE 1  
USE BY SELECTED INSTITUTIONS, AUGUST 2001

Institution	heavy users <sup>a</sup>	AAS Members <sup>b</sup>	unique reads <sup>c</sup>
Harvard-Smithsonian	236	250	8085
Space Telescope	126	163	5271
CalTech	173	196	5589
Cornell	33	52	899
European Southern Obs.	385	18	11274
Total worldwide	10532	6429	350404

<sup>a</sup>Unique users who have read ten or more articles during the month

<sup>b</sup>AAS (2001)

<sup>c</sup>Number of unique user-paper pairs

ceed the actual number of different people using the system; a person who logs in from work and from home would count twice, but any number of people using a library computer would count as one; also a person who used more than one of our dozen mirror sites would be counted more than once. The monthly usage for October 2001 was 51,960 users.

This number may be compared to 8,692 members of the International Astronomical Union (IAU) (IAU 2001), the largest organization of professional astronomers. There were 10,677 different authors listed in the papers published in 2001 by the seven major astronomy journals, 5576 of these were listed as (co-)author on more than one paper. Independent of how many actual users the ADS has, we believe nearly every working astronomer uses the ADS very regularly.

Table 1 compares the number of unique users who read ten or more articles during August 2001 using the ADS to the number of members of the American Astronomical Society for some selected astronomical institutions. The number of AAS members is similar to the number of heavy ADS users for the US organizations; more than twice as many users are present at each institution, but they use the ADS less frequently, the heavy users account for about 85% of the total use of the system.

The number of unique reads represents the

number of unique user-article pairs in a month, thus if a single user reads the same article twice, it only counts once. This is the most conservative estimate of number of articles read in the system. For heavy users the median number of articles read per month is 22, with very little change among various organizations or subgroups. This is the basis for our claim that the typical working astronomer, on average, uses the ADS every working day.

As the numbers for the European Southern Observatory, which is located near Munich, demonstrate, the use of the ADS is not limited to organizations within the United States. Three fifths of all ADS use comes from outside the United States; this will be explored in the next section.

Tenopir, et al. (2003) independently discuss the degree to which the ADS is used by astronomers.

#### 4. ADS as indicator of the worldwide research effort

Astronomy is a worldwide enterprise, and, as probably the least practically useful of all sciences, is perhaps the best indicator of how pure research is done internationally. As the ADS use is overwhelmingly by astronomy researchers, a country by country comparison of ADS use can yield insights into the factors which influence the world's pure research.

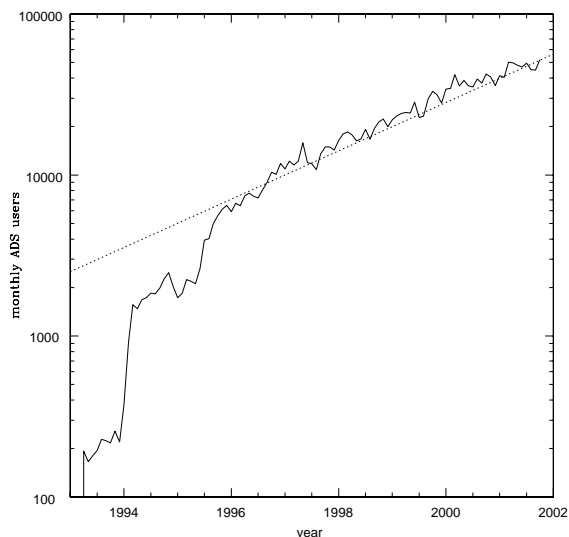


Fig. 2.— The number of unique users of the ADS each month. The dotted line represents a 2 year doubling time.

#### 4.1. ADS use and GDP

Certainly one factor which influences the research done in a country is the wealth of that country. Figure 3 shows the ADS use per capita vs. the GDP per capita. There is clearly a trend. The center line shows the relation where ADS use per capita is proportional to GDP per capita squared; the lines to each side are separated by a factor of  $\sqrt{2}$  in per capita GDP.

Taking ADS use as a proxy for basic research we obtain directly a simple relation for the amount of basic research done in a country:

$$BasicResearch \propto (GDP)^2 / Population \quad (1)$$

The ADS use is obtained by counting the number of entries in the query log (this is approximately twice the true number of requests to the system) made during the year 2000, and the GDP is by the purchase power parity method (CIA 2001). Most queries can be automatically resolved to the internet host address, but about 20% cannot; the IP addresses which do not resolve are systematically more frequently found in the less industrialized countries. We have resolved by hand (to the country level) all class B and class C

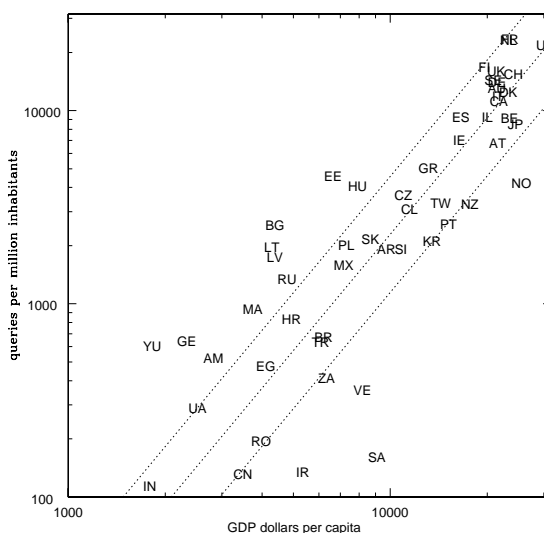


Fig. 3.— The per capita GDP of a country vs. the ADS use per million inhabitants in that country. The symbols are the ISO symbols for each country.

IP subnets with more than 1,000 queries during the year 2000, this procedure only significantly changed the data for two countries, Egypt and Morocco. By this process we can be certain that we have not missed any large group of astronomers (1,000 queries is a typical amount for a single very active user); we have not resolved about 10% of the queries, and can be certain that the results for some countries with low usage are systematically underestimated.

Comparing the GDP figures from the CIA (CIA 2001) with those from the Economist Magazine (Economist 2001) shows that these can differ by a factor of two for some developing countries, and by as much as 30% even in industrial countries.

Figure 3 contains only countries where the number of ADS queries is equal or greater than 1,737, which is the average number of queries per member of the IAU, and is about equal to the use of two active users. There are several things which can be seen in the plot. First, notice that the United States is not the largest per capita user of the ADS; France (FR) and the Netherlands (NL) are; their symbols obscure each other on the plot. Also notice that while the difference in per capita income between the richest and poorest countries

is a factor of ten to fifteen, the difference in per capita ADS use between these countries is close to three hundred.

Next notice that the countries to the left of the dotted lines, those which perform more research per capita than their GDP per capita squared would suggest, are, with one exception (Morocco, MA) all eastern European countries which have undergone substantial economic and political change in recent years. It is possible that in the face of such large historical changes GDP is not a fully accurate measure of the total wealth of a country, which would also include existing infrastructure.

Also notice that the four countries to the right of the dotted lines, those which perform less research than expected, are all oil producing states. It is possible that the (historically) recent increased GDP due to oil revenues in these countries is not a true measure of their actual long term wealth.

**4.2. ADS use and IAU membership**

Another factor which affects the amount of research done in a country is the number of researchers in that country. Again using astronomy as an indicator of the pure research effort we will take the membership in the IAU on a per country basis (IAU 2001) and compare that to the amount of ADS use in each country.

One might naively assume that on average the per astronomer use in each country would be constant; the average astronomer would do the average amount of research independent of location. However, figure 4 shows for each country the number of ADS queries per IAU member as a function of GDP per capita. In fact there is a clear trend, the dotted line shows the relation where ADS use per IAU member is proportional to GDP per capita, hence the productivity of individual astronomers is not independent of location. The dotted line is not a fit, and the scatter in this relation is too large to derive a parameterization. The dotted line is perhaps the simplest relation which is consistent with the data.

**4.3. IAU membership vs. GDP**

Combining the relations shown in figure 3 (ADS use per capita is proportional to GDP per capita

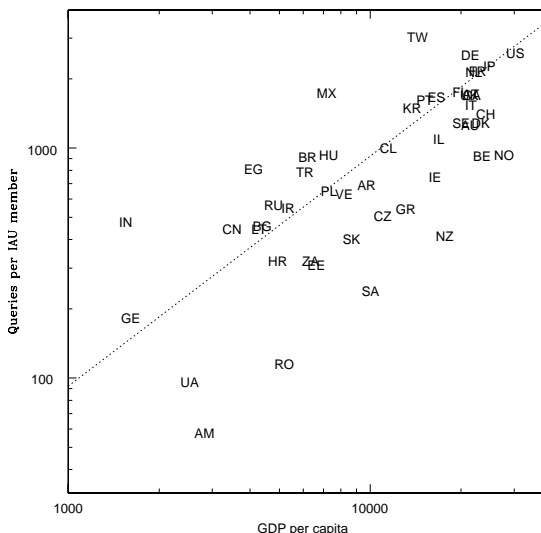


Fig. 4.— The per capita GDP of a country vs. the ADS use per the number of IAU members in that country. The symbols are the ISO symbols for each country.

squared) and figure 4 (ADS use per IAU member is proportional to GDP per capita) one obtains the relation that IAU membership is proportional to GDP. This relation can also be obtained in other ways, and is obviously independent of the ADS. Figure 5 shows the relation; the central dotted line represents the relation one astronomer per \$4,300,000,000 which is the total world GDP divided by the number of IAU members.

The trend in these data is clear. Nearly all countries on the plot follow the relation, the principal exceptions being Indonesia, Thailand, and Pakistan (ID, TH, and PK). The countries, however, do not seem to form a single linear relation. The two flanking lines, which are separated from each other by a factor of three, seem to better describe the distribution than the single average. We suggest that this bifurcation is real, and represents the cultural difference between western nations and eastern nations with regard to support of basic research. Additionally some countries perform essentially no astronomy; they are primarily from southeast Asia (excluding India) and sub-Saharan Africa.

If one divides the data by the mean line down

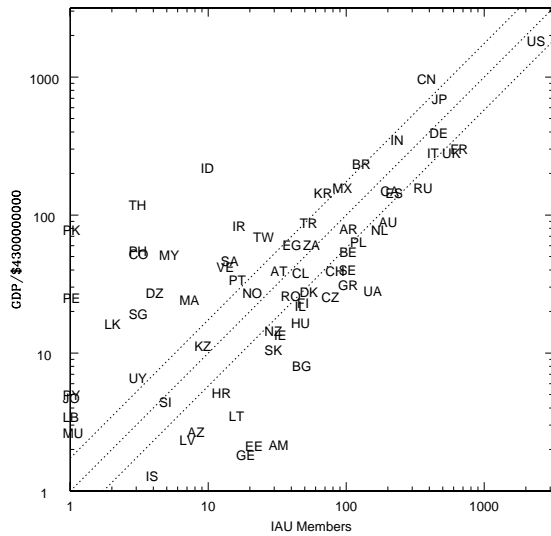


Fig. 5.— The GDP of a country in units of \$4,300,000,000 vs. the number of IAU members in that country. The symbols are the ISO symbols for each country.

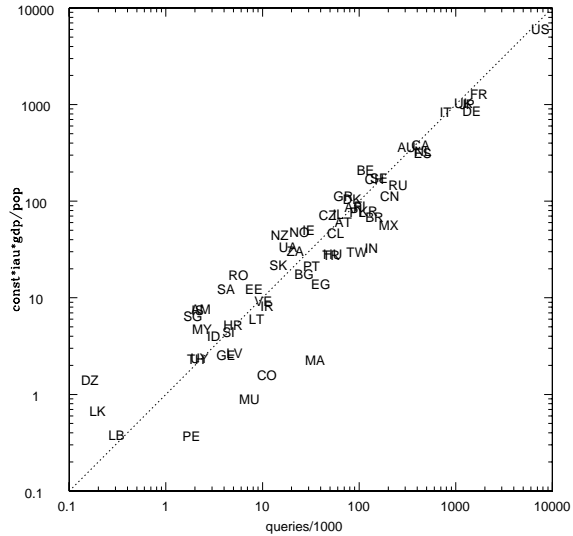


Fig. 6.— The number of astronomers times the per capita GDP vs. ADS use for each country. The symbols are the ISO symbols for each country.

the center, one finds that 31 European countries are below the line and three above. One also finds that seventeen Asian countries are above the line, and none are below. We thus propose:

$$Scientists = \frac{c}{k}GDP \quad (2)$$

where for astronomy

$$c = \begin{cases} \sqrt{3} & \text{if european culture;} \\ \frac{1}{\sqrt{3}} & \text{if asian culture;} \\ 0 & \text{otherwise.} \end{cases}$$

and

$$k = \$4,300,000,000$$

*Scientists* is the number of scientists in a country, GDP is the GDP of that country, k is the mean GDP per scientist worldwide, and c is a cultural factor which differs among countries.

#### 4.4. A model for worldwide basic research

Rearranging the relation shown in figure 4 we obtain the following model for the research done in a country:

$$BasicResearch \propto Scientists \frac{GDP}{Pop} \quad (3)$$

The amount of basic research done in a country is proportional to the number of scientists times the per capita GDP.

Figure 6 shows this model; the dotted line represents the same mean proportionality constant as in the line in figure 4. The model in equation 3 provides a reasonably accurate prediction of the research output of a country for countries differing in research output over a factor of ten thousand.

#### 4.5. Discussion

Combining equations 2 and 3 we get a simple picture of the major factors affecting research worldwide. The number of scientists in a country is just proportional to the GDP of that country, except that Asian and European countries have a different proportionality constant, by a factor of three (and some countries simply do no astronomy); and the amount of research done in a country is proportional to the number of scientists in that country, times an efficiency factor which is just the GDP per capita.



This model for the research of nations is essentially a quantification of the Matthew Effect for Countries (Bonitz 1997), an extension of the Matthew Effect (Merton 1968) which essentially states that the system of rewards in science is that the rich get richer and the poor stay poor.

According to this model two countries with the same GDP (for example India and France) will have the same number of scientists (ignoring the cultural factor). The amount of research these scientists perform, however, differs by the ratio of the per capita GDP for the two countries, more than a factor of ten in the case of India and France.

## 5. Readership as a function of age

Because the use of the ADS is now the dominant means by which astronomers access the technical literature (see sections 2 and 9) the ADS usage logs can provide a uniquely powerful view of the way an entire discipline (astronomy) uses the technical literature. In this section we will examine the obsolescence (e.g. White and McCain (1989), Line and Sandison (1975)) of the technical literature of astronomy as a function of article age based on the actual readership of an article. This is an extension and reexamination of the work explored in Kurtz et al. (2000).

We use, as our basic data source, the log of all article “reads” using the ADS between January 1st and August 20th, 2001. We define a “read” as every time a user who has access to a list of articles, their dates, journal names, titles and authors (such as in figure 1) chooses to view more information about an article. Currently 50% of these “reads” are of the abstract, 38% are of one of the forms of whole text, 8% are of the citation list, and the rest are distributed amongst ten other options. There are more than 4.2 million “reads” in this log.

For this study we extracted reads for the three major U.S. astronomy journals; *The Astrophysical Journal*, *The Astronomical Journal*, and *The Publications of the Astronomical Society of the Pacific*. All three of these journals have been stable over the past century and are currently among the most important astronomy journals. All have had their full text versions beginning with their first issues available on-line through the ADS since well before the beginning of the reporting period.

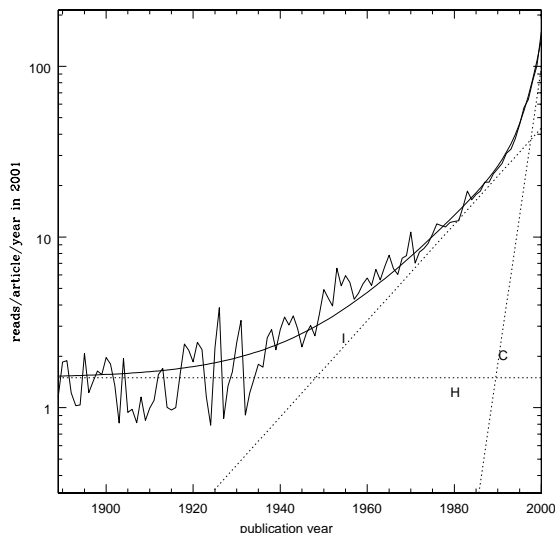


Fig. 7.— The average number of reads per article per year for three U.S. astronomy journals. The thin line is the actual data, the thick line is the model in the text, and the three dotted lines represent the three components of the model.

These journals accounted for slightly more than 1.8 million reads in the first 7.66 months of 2001.

### 5.1. The obsolescence model for reads

Figure 7 shows the average number of reads per article per year for these three journals as a function of publication year. This shows more than a full century from the first issue of *The Publications of the Astronomical Society of the Pacific* in 1889 through 2000.

Figure 8 shows an expanded view of the last 25 years of data from figure 7. The dotted lines show the relevant three components of the four component readership model of Kurtz et al. (2000), as modified here. In this model, research article readership ( $R$ ) is parameterized by the sum of four exponential functions with very different time constants. We associate these four functions with four different modes of readership: Historical ( $R_H$ ), Interesting ( $R_I$ ), Current ( $R_C$ ) and New ( $R_N$ ). The New ( $R_N$ ) mode, which corresponds to the newly arrived (either on-line or in the mail) issue, cannot be parameterized by the data in figures 7 and 8. The Historical ( $R_H$ ) mode we actually parame-

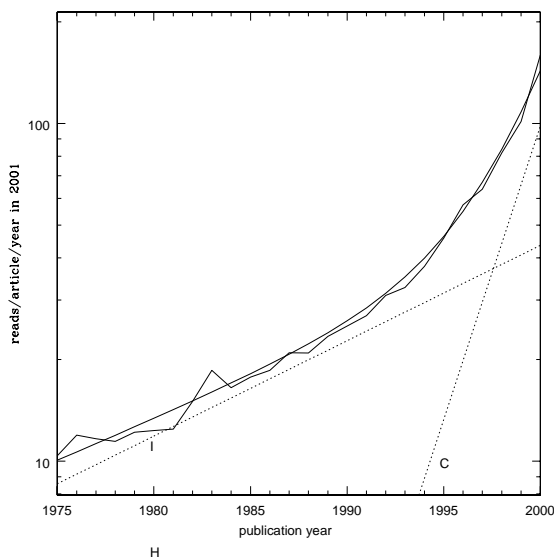


Fig. 8.— An expanded view of Figure 7 showing the most recent 25 years. Note that the model fits the actual data very well.

terize as a constant,  $H_0$ , we leave the exponential form in equation 4 (with  $k_H = 0$ ) because other combinations of multiplicative and time constants can also be found which fit the data well, including some combinations with  $k_H \neq 0$ .

$$R = R_H + R_I + R_C + R_N \quad (4)$$

where

$$R_H = H_0 e^{-k_H t}$$

$$R_I = I_0 e^{-k_I t}$$

$$R_C = C_0 e^{-k_C t}$$

$$R_N = N_0 e^{-k_N t}$$

and

$$H_0 = 1.5; k_H = 0$$

$$I_0 = 45; k_I = 0.065$$

$$C_0 = 110; k_C = 0.4$$

$$N_0 = 1600; k_N = 16$$

$t$  = time since publication in years

The three longer term functions,  $R_H$ ,  $R_I$ , and  $R_C$  are parameterized to fit the data shown in figures 7 and 8. The  $R_N$  function is included for completeness;  $k_N$  is taken from Kurtz et al. (2000),

and  $N_0$  obtained by assuming  $k_N$  is correct, and ascribing all readership of the *Astrophysical Journal* electronic edition which does not originate with the ADS to the N mode. This is a very crude approximation, but the three component ( $R_H$ ,  $R_I$ , and  $R_C$ ) model for archival readership is not affected by the N mode usage, which fades very rapidly following publication.

The three mode model is not unique, but does, as figures 7 and 8 show, provide a very good fit to the existing data. No model consisting of only two exponential functions can fit both the recent and historical data, as comparing the two figures makes clear.

Most studies of obsolescence find that the use of the literature declines exponentially with age, and parameterize this with a single number, often called the “half-life,” which is related to the coefficient in the exponent by  $\text{half-life} = \log_e(2)/k$ , the point where the use of an article drops to half the use of a newly published article. There are several other definitions of half-life in the literature, we use this one. Thus the Historical ( $R_H$ ) component of equation 4 does not have a half-life; the half-life of the Interesting ( $R_I$ ) component is 10.7 years; the half-life of the Current ( $R_C$ ) component is 1.7 years. Kurtz et al. (2000) estimate the half-life of the New ( $R_N$ ) component at 16 days.

Several studies (e.g. Egghe (1993) and references therein) decompose the exponential decay in use into the product of an intrinsic decay and the general growth of the literature. The results presented here are for the mean current use per article published as a function of time since the present, thus we measure directly the intrinsic decay. Kurtz et al. (2000) show the growth of the astronomy literature has been 3.7% per year, measured in terms of number of papers published over the past 22 years.

The total number of papers read over time in each mode is just the integral of the function from zero to infinity, which for a negative exponent is just the ratio of the two constants:  $H_0/k_H = \infty$  reads (one and a half reads per year forever);  $I_0/k_I = 818$  reads;  $C_0/k_C = 275$  reads;  $N_0/k_N = 100$  reads. This assumes no growth in the number of reads; if the number of reads per year increases long term at the same rate, 3.7%, at which the number of publications is now increasing, then the constants in the exponents would all

be increased by 0.037. This would have very little effect on the integrals of the  $R_N$  and  $R_C$  functions, but would more than triple the articles read in the  $R_I$  mode; and the  $R_H$  mode would grow apace with the growth in the number of reads.

## 5.2. Discussion

Beginning with Burton and Kebler (1960) there have been a number of studies (see White and McCain (1989) for a review) which suggest that the obsolescence function consists of the sum of two exponentials, which Burton and Kebler (1960) attribute to “classic” and “ephemeral” papers; parameterizations (e.g. Price (1965)) tend to be similar to our  $R_H + R_I$  functions.

If we ignore the  $R_N$  component, which neither this study, nor any of the other studies of obsolescence could see, we still very clearly find three separate components to the obsolescence function. Why have these three components not been seen until now?

We suggest that the data available to previous studies have not been adequate to see these subtle effects. Most studies have used citation data to determine the obsolescence function. Because it takes time after a paper is published for it to be cited (e.g. section 6) the peak in the  $R_C$  mode is obscured in citation data. Also citation studies have substantial problems accounting for the growth of the literature, which has not been at all constant over the past century. Related to this is the determination of the size of the sample universe (the number of relevant papers to the study) at past times.

There are certainly other possibilities, perhaps the obsolescence function is different for reads and cites, and perhaps the very existence of the ADS has changed the way the literature is used. We will explore these questions further in section 6.

The reason why readership studies have not seen the three component nature of archival readership which we see, we suggest, is that the data available in such studies have been too sparse. The largest astronomy library, the Center for Astrophysics Library, has a reshelve rate of about 1,000/month (Coletti 1999), which is less than 0.2% of the rate of reads in the ADS. Additionally many astronomers keep (and use) their own paper copies of recent journals, which would suppress the

$R_C$  mode in library use.

## 6. The relationship between reads and cites

Central to bibliometrics is the study of citations (Garfield 1979), and central to the study of citations is the so called normative assumption (Liu 1993) that “the number of times a document is cited ... reflects how much it has been used...” (White and McCain 1989). There have been many articles suggesting problems with citation studies (e.g. MacRoberts and MacRoberts (1989)), and many articles defending them (e.g. Small (1987)). White (2001) and Phelan (1999) discuss these issues.

The readership data discussed in section 5 provide a totally independent, direct new measure of “how much [an article] has been used.” Comparing the readership statistics with citation measures will show the similarities and differences between citations, which are an indirect measure of use, but, some would argue, a direct measure of usefulness, and reads, which are a direct measure of use, but perhaps an indirect measure of usefulness. Here we expand considerably on the comparison presented in Kurtz et al. (2000).

### 6.1. The mean relationship between reads and cites

While there have been many dozens of studies on obsolescence using citations, and many dozens more using readership as determined by using library circulation statistics (see White and McCain (1989) for review), there are very few studies comparing the two methodologies over the same data. Tsay (1998) compared the readership obsolescence function (obtained by reshelving statistics) for a number of medical journals with the citation obsolescence function for the same journals. He found the half-life of the readership function was significantly shorter than the half-life of the citation function. Tsay (1998) reviewed the literature and found only one previous comparable study; Guitard, in 1985 (discussed in Line (1993)), using photocopy requests as the use proxy, found the citation half-life shorter than the readership half-life.

We have only found two other studies. Cooper and McGregor (1994), also using photocopy data,

found citation half-life substantially longer than the use half-life; also they found “no correlation between obsolescence measured by photocopy demand and obsolescence measured by citation frequency.” Satariano (1978) used the questionnaire method to find “citation patterns reflect a cross-disciplinary focus that is not found in the journals most often read.”

We believe Kurtz et al. (2000) contains the first study using a data-set large enough to show the similarities and differences between the two obsolescence functions. Here we use a substantially improved data-set; we intend this section to supersede the study in section 6.2 of Kurtz et al. (2000).

### 6.1.1. Synchronous relation

Kurtz et al. (2000) found that the instantaneous obsolescence function for articles from the recent technical astronomy literature as measured by citations is simply equal to a proportionality constant times the function measured by reads times an exponential ramp-up to account for the time delay from when an article is first published to when an article which cites that article is published:

$$C = cR(1 - e^{-k_D T}) \quad (5)$$

where

$$c \approx \frac{1}{20}; k_D = 0.7$$

The proportionality constant,  $c$ , represents the number of citations per read. This changes with the (always incomplete) citation databases, and with time, as ADS use increases (see section 3). Currently we estimate that the average paper is read about twenty times using the ADS for every time it is cited. In comparing the citation and reads obsolescence functions we have adjusted  $c$  to provide the best fit to the samples.

Figure 9 compares the reads and cites obsolescence functions for recent articles. The readership data are for articles from *The Astrophysical Journal*, *The Astronomical Journal*, *The Publications of the Astronomical Society of the Pacific*, and *The Monthly Notices of the Royal Astronomical Society* which were read between 1 January 2001 and 20 August 2001. The citation data are taken from those four journals and both *Astronomy & Astrophysics* and *Nature*, where the publi-

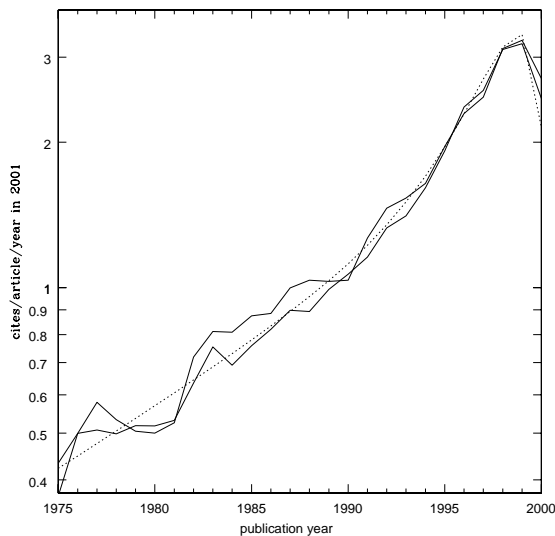


Fig. 9.— A comparison of the  $C = cR(1 - e^{-k_D T})$  model with the actual citations from the 2001 sample for papers from the most recent 25 years. The thick line is the actual citations, the thin line is the model, using the actual reads, and the dotted line is the model using the reads model, equation 4.

cation date was also between 1 January 2001 and 20 August 2001. Only citations to one of the four journals in the readership sample were taken; the data contain 45,000 citations.

As can be seen from figure 9 the citation function follows the reads function very closely. In particular the  $R_C$  function (section 5.1) clearly has an analog in the citation data, despite the suppression of the steep increase compared with the raw reads due to the exponential ramp-up. The change in slope in the citation function seen beginning about 1994 is exactly what is predicted from the reads function; the number of citations in 1998 and 1999 are more than 40% above that expected by an extrapolation of the exponential decay seen between 1975 and 1990, a decay which corresponds very closely to the  $R_I$  function. We suggest this shows that the citation derived obsolescence function has two components with exactly the same parameters as the two mid-range (in time) readership functions.

To examine the obsolescence function over a

longer time period we use a different data-set of citations. We take all citations to the four journals in the readership sample from articles published between 1 January 1995 and 20 August 2001 in the ADS database. The data contain 625,000 citations.

We continue to use as our comparison the year 2001 reads sample. Clearly papers published in 1995 could not have cited papers published in 2000, so comparison with recent obsolescence is impossible (this comparison is in figure 9). We use these data exclusively to examine the long term behavior of the obsolescence function.

Figure 10 shows the long term obsolescence function obtained from citation data compared with the readership function. They clearly are **not** the same. The citation function follows the  $R_I$  function, but not the  $R_H + R_I$  function. This is not a statistical fluke based on having a small number of citations; the number of citations in the period from 1889 to 1940 which are “missing” from the citation function exceeds 5,000. In the year 1900, for example, there were 18 citations in the six year sample, while about 150 would be expected, were the  $R_H$  mode to produce citations at the same amplitude as the  $R_I$  mode.

We are therefore driven to the conclusion that:

$$C = c(R_C + R_I)(1 - e^{-k_D T}) \quad (6)$$

where

$$c \approx \frac{1}{20}; k_D = 0.7$$

for research articles in the astronomy literature.

There are a number of possible reasons for the citation obsolescence function to be different from the reads function. There are also a number of possible reasons why the citation obsolescence function measured here does not show the  $R_H$  component, whereas this component is seen in other citation based obsolescence functions, beginning with Price (1965). We see no clear candidate explanation which accounts for both differences, however.

### 6.1.2. Diachronous relation

As a further test of the citation model in equation 6 we compare the model with the citations to articles published in four different years, 1983, 1986, 1990, and 1992 by the four main journals in

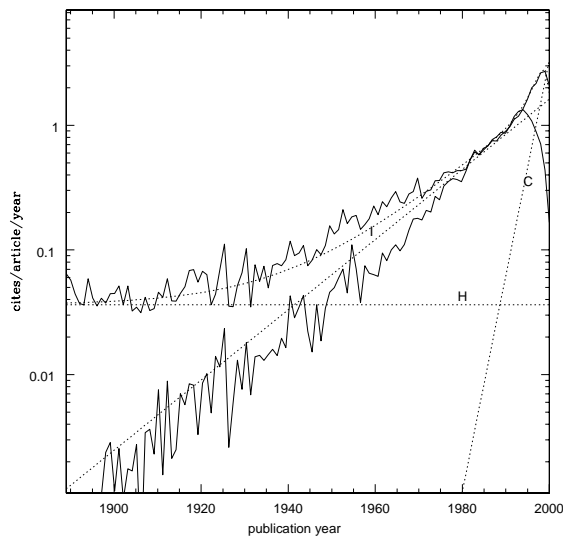


Fig. 10.— A comparison of the  $C = cR(1 - e^{-k_D T})$  model with the actual citations for papers from the six year sample for the last 111 years. The thick line is the actual citations, the thin line is the model, using the actual reads, and the dotted lines are the modified reads model from equation 4 and its components.

astronomy; *The Astrophysical Journal*, *The Astronomical Journal*, *The Monthly Notices of the Royal Astronomical Society*, and *Astronomy & Astrophysics*. We use all the citations in the ADS citation database; each year has between 67,000 and 75,000 citations to articles from these four journals.

Figure 11 shows the comparison. The thin lines are the actual number of citations each year to the articles, normalized so that the the average citation rate over the first five years after publication is exactly one. The citation rates go to zero when the timespan following publication reaches the present (or more accurately 20 August 2001); thus one can tell which line represents which year, 1992 goes to zero first, 1983 last.

The thick line is the citation model of equation 6, using exactly the same parameters as in equation 4, modified to account for a 3.7% yearly growth in the literature.

It can be noted that the model matches the data as well or better than the curves for the different

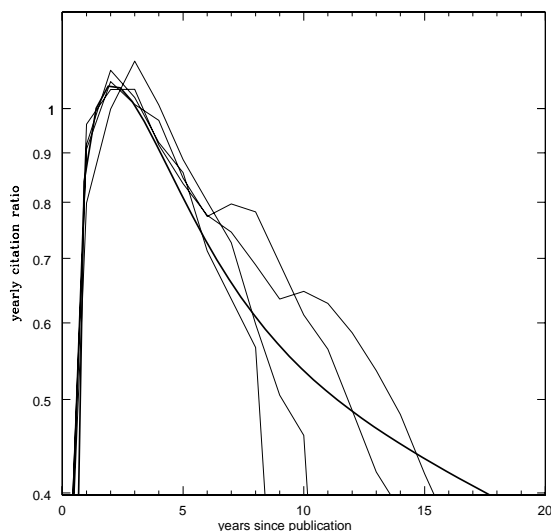


Fig. 11.— A comparison of the  $C = c(R_C + R_I)(1 - e^{-k_D T})$  model with the actual citations for papers published in 1983, 1986, 1990 and 1992. The thin lines are the actual data for the four different years, the thick line is the model, using the  $R_C$  and  $R_I$  components of the reads model of equation 4 and assuming the 3.7% yearly growth rate of Kurtz et al. (2000).

years match themselves. While these data may be fit with a different citation function, one where the  $R_C$  component is zero, the slope of the required  $R_I$  function necessary to fit these data is very much too steep to fit the long term decline shown in the data in figure 10. To fit the data in figure 11 with a single  $R_I$  function it would have to have a slope  $k_I = 0.15$  which is completely excluded by the citation data shown in figure 10. Also the function would then fit only the 1990 data well, the one with the offset peak. We believe the offset peak is caused by a mean three weeks delay in the time of actual publication compared with the publication date in that year, and that the other three years better represent the true function.

Therefore we conclude that this comparison also provides strong evidence for a model where citations follow the function  $C = c(R_C + R_I)(1 - e^{-k_D T})$  where the  $R_C$  and  $R_I$  modes are those usage behaviors seen in the study of the readership data in section 5.1.

### 6.1.3. Discussion

We have shown that the citation rate as a function of time is equal to a constant times the sum of two modes of the readership function. There is no *a priori* reason why the constant  $c$  in equation 6 should not actually be a function of time. Why should the number of citations per read (about 0.05) be constant, independent of the age of the article?

Examining figures 9 and 10 we see that if  $c$  is a function of time it cannot change by more than about 1% per year. This is an extraordinary result, it says that within the (small) measurement error the  $C$  function and the  $R_C + R_I$  function must be measuring exactly the same thing, the mean usefulness of journal articles as a function of time.

The private act of reading an article entails none of the various sociological influences that the public act of citing an article does (Seglen (1997) lists several of these factors). This suggests that in the mean these factors do not influence the citation rate.

Unless the sum of all the various sociological influences as a function of time is exactly the same as the usefulness of articles as a function of time the existence of these influences would cause  $c$  not to be constant. That  $c$  is constant means that at every age the total effect of these various influences is zero.

We therefore assert that we have proven that the normative theory of citing (Liu 1993) is true in the mean.

## 6.2. The relationship for individual papers

### 6.2.1. All articles in the database

While the citation rate may be a direct measure of usefulness in the mean, there are clearly other factors at play for any individual article. Certainly citations are not the only valid measure of usefulness; newspapers, for example, are very useful but not often cited.

In this section we will compare reads and cites on a per article basis. We believe this is the first time data of this sort have been published.

Table 2 shows the relationship between reads and cites for all articles in the ADS database. The

TABLE 2  
READS VS CITES IN 2000 FOR ALL ARTICLES<sup>a</sup>

NC\NR	0	1	2	4	8	16	32	64	128	256	512	1024	2048	total
0	20.71	17.44	16.72	16.08	15.29	14.14	12.86	11.40	9.19	5.75	0.00	0.00	0.00	2133024
1	12.03	11.00	11.82	12.56	12.90	12.74	11.90	10.82	9.17	6.07	0.00	...	...	36621
2	9.32	8.55	9.65	10.83	11.87	12.43	12.25	11.35	9.82	7.19	0.00	...	...	21418
4	5.81	5.21	6.30	7.83	9.40	10.95	11.68	11.39	9.95	7.64	3.46	0.00	...	10217
8	2.32	2.00	3.00	3.58	5.93	7.83	9.63	10.40	9.73	7.69	4.32	...	...	3532
16	0.00	0.00	0.00	1.00	3.46	4.81	5.78	7.84	8.52	7.47	4.64	...	...	896
32	...	...	...	...	1.00	2.00	3.46	4.09	5.78	6.29	4.46	0.00	...	190
64	...	...	...	...	...	...	2.00	2.00	1.58	4.09	3.58	2.00	...	44
128	...	...	...	...	...	...	0.00	1.00	...	0.00	0.00	1.00	0.00	8
total	1714338	179938	112360	77346	52260	32681	20256	11392	4328	946	94	9	2	2205950

<sup>a</sup>In terms of the base 2 logarithm of the cross-tab counts.

reads and cites refer to articles read during calendar year 2000 and to articles cited in papers published during calendar year 2000. Table 2 is formatted as follows: the horizontal direction corresponds to the number of reads and the vertical direction shows the number of cites. The data are binned in factors of two, so for example, the sixth column shows the number of citations for articles which were read between 16 and 31 times and the fifth row shows the number of reads for articles which were cited between 8 and 15 times. The actual numbers in the cells are the base 2 logarithm of the actual counts, thus the number of articles which were read between 16 and 31 times and which were cited between 8 and 15 times is  $2^{7.83} = 227$ .

Looking at table 2 we can see several things, first the vast majority of articles in the ADS database ( $10^{20.71} = 77.5\%$ ) were neither read nor cited during the year 2000. Nearly 97% of all articles in the database were not cited during this period. The most likely number of times which an article was cited was zero for articles which were read fewer than 128 times. 72,926 different articles in the database were cited during this period, while 491,612 different articles were read. The large number of unread articles is because the ADS contains a very large physics data set (it is larger than the astronomy data set); overwhelmingly the ADS is used by astronomers, the physics data are not yet heavily used. At the time these

data were captured the ADS did not contain the majority of citations to articles in the physics literature (it does now, however); it did contain most of the citations from the astronomy literature to the physics literature.

Looking at the number of cites (the left column) and finding the most likely number of reads for a given number of cites we find that the most likely number of reads for articles cited zero times is zero, for articles cited 1 time is 8-15, for articles cited 2-3 times is 16-31, etc. The maximum in the readership rate given the citation rate moves very nearly as number of citations times eight. Looking at the cells to the right and left of these maxima we see that the average decline is somewhat less than a factor of two (a difference of one in the base 2 log) for each cell, where each cell is a factor of two in number of reads.

The number of citations are thus a good predictor of the number of reads, with the distribution approximately normal in the log, and with the standard deviation about a factor of two (one in the base 2 log). The same cannot be said of the number of reads, they clearly make a very poor predictor of the number of citations. Looking for example at 64-127 reads the most likely number of citations is zero, but the cell with 2-3 and the cell with 4-7 citations are each close to as full.

With nearly seven times as many different articles being read as cited, the factors which cause

someone to read an article are not always the same as the factors which cause someone to cite an article. This is also apparent in that the cell with the most likely number of reads, given a number of cites, contains, in nearly every case, fewer papers than any of the less well cited cells at that readership level.

The most important factor which differentiates reads from cites is youth; as parameterized by the factor  $(1 - e^{-k_D T})$  in equation 6. The ratio of reads to cites (in the year 2000, using the ADS) for papers published in 1995 is 17.4, and in 1985 is 17.1. The ratio for papers published in 2000 is 143. 14.5% of all reads in 2000 were to papers published in 2000, but only 2.5% of all cites were to papers published during the calendar year the citing papers were published (2000). 95% of all papers which were read 256 or more times, but which were cited fewer than four times were published within 1.5 years of the end of 2000.

The second most important factor which differentiates reads from cites is the type of article. In 1995 the *Astrophysical Journal*, published 2,258 full length refereed articles. During 2000 2,250 (99.6%) of these were read and 1,541 (68%) were cited. Also in 1995 the *Bulletin of the American Astronomical Society* published 1,272 unrefereed abstracts. During 2000 1,152 (91%) of these were read, but only 22 (1.6%) were cited.

The third factor differentiating cites from reads is the actual content of each article. The most cited and read papers during 2000 make this point. The most cited paper during 2000 (Landolt 1992) is also the second most read paper during this period. Landolt (1992) is a prototypical highly cited paper; it contains the basic calibration data for a fundamental measurement technique.

The most read article during 2000 (Trimble and Aschwanden 2000) was not cited during that time. This is a prototypical newspaper type article, it contains an extensive review of the past year's literature in astrophysics, part of a yearly series of articles by the same authors. While it might be expected that this article would not be cited during the year following its publication it still has never been cited as this present article is written, 2.5 years later, nor have the two articles which followed it or the article which preceded it in the same series (Trimble and Aschwanden 1999, 2001, 2002) each of which was (is) the most read article

by ADS users in the year following its publication.

The final factor which differentiates reads from cites is age; the  $R_H$  component of readership has no counterpart in the citation function. It is likely that this component of the readership represents papers which are read simply for their historical interest, not because they directly influence a current research problem.

#### 6.2.2. The 1990—1997 *Astrophysical Journal*

Table 3 is similar in format to table 2, but only includes reads and cites during 2000 to papers published in the *Astrophysical Journal* in the years 1990—1997. This eliminates many of the systematic causes of differentiation between reads and cites, such as youth, age, and article type seen in table 2.

The most obvious difference between tables 2 and 3 is that most of the articles represented in table 3 are heavily used, while most of the articles in the whole database are not used at all. 78% of the articles in the whole database were not read in 2000 and 97% were not cited, but only 0.6% of the 1990—1997 *Astrophysical Journal* articles in the database were not read, and 36% were not cited. Recent *Astrophysical Journal* articles are at the core of modern research in astronomy.

The number of cites in table 3 predicts the number of reads to about the same accuracy (a factor of two) as seen in table 2 for the whole database. The number of reads shown in table 3, however, is also a reasonable predictor of the number of cites (also to about a factor of two), which it is not for the whole database.

For the homogeneous sample of standard journal articles used here, this again demonstrates that the normative theory of citing (Liu 1993) is true in the mean; the scatter about this mean is a multiplicative factor of about two, and contains within it all the various sociological, political, and scientific factors which cause variations for individual papers.

Twelve (out of 16,557) of the *Astrophysical Journal* articles in table 3 were cited more times than they were read, 11 were cited once but not read, and 1 was cited twice and read once. This suggests two things. First: ADS users must represent all the subfields of astronomy which are published by the *ApJ*. If there were any large subfield



TABLE 3  
READS VS CITES IN 2000 FOR 1990-1997 *ApJ* ARTICLES<sup>a</sup>

NC\NR	0	1	2	4	8	16	32	64	128	256	512	1024	2048	total
0	6.64	7.17	8.89	10.17	10.79	10.61	9.28	6.66	2.81	...	...	...	...	5922
1	3.46	4.00	6.21	8.36	9.69	10.29	9.64	7.38	3.46	...	...	...	...	3479
2	...	0.00	4.39	6.99	9.04	10.30	10.32	8.78	5.00	...	...	...	...	3688
4	...	...	...	3.91	6.52	8.84	9.96	9.38	6.70	1.58	...	0.00	...	2332
8	...	...	...	...	1.00	5.04	7.88	8.70	7.37	3.17	0.00	...	...	863
16	...	...	...	...	...	0.00	2.58	6.04	6.79	5.32	...	...	...	224
32	...	...	...	...	...	...	...	1.58	3.70	4.64	1.00	...	...	43
64	...	...	...	...	...	...	...	...	0.00	1.00	1.00	0.00	...	6
total	111	161	569	1622	3210	4567	3927	1860	444	79	5	2	0	16557

<sup>a</sup>In terms of the base 2 logarithm of the cross-tab counts.

of astronomers who did not use the ADS, the papers they read and reference would show up in table 3 as cited but not read. Second: astronomers overwhelmingly read the articles which they reference. If there were any substantial population of articles which were being *pro forma* cited, but not read they would also appear in table 3.

### 6.2.3. How historical cites influence reads

As shown in section 5 the maximum rate at which articles are read occurs immediately following their publication, and then declines with time. However astronomers learn of the existence of an article during the first year or so following publication, they do not learn of it by a citation, as none exists at that time. It is reasonable to ascribe a causality in this situation: following publication an article is cited because it has been read.

Later in the life of an article this causation is often reversed: an article is read because it has been cited. Pointing readers of an article to other articles of interest to read is one of the principal functions of citations.

Table 4 shows the number of reads during the two year period 2000—2001 for articles published in the *Astrophysical Journal* during the years 1950—1959 versus the **total** number of citations for these articles from the ADS citations database.<sup>3</sup> Very clearly there is a strong correla-

tion of the readership rate of articles with the total number of citations for that article.

The total number of citations can predict the readership rate about as well as the citation rate predicts the readership rate (to within about a factor of two) in the samples of tables 2 and 3. The readership rate is also a predictor of the total number of citations, again to about a factor of two, similar to the ability of the readership rate of 1990—1997 *Astrophysical Journal* articles to predict their current citation rate. Also, as with the 1990—1997 *Astrophysical Journal* articles, the distribution of citations as a function of reads is not a symmetric normal distribution, but is skewed toward fewer citations. Unlike the effect with the whole database (table 2) this does not overwhelm the predictive power of the reads, however.

Although papers with higher total citations tend strongly to be the papers most read, this is not due to the existence of more links to these papers from the on-line reference lists. By examining the reads of *Astrophysical Journal* articles by unique individuals (as determined by their cookie) which follow these individuals accessing the reference list of a different article, as a function of the

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publication and *Astronomy & Astrophysics* began publication. The ADS citation database does not yet contain citations from these earlier European journals, perhaps 30% of the expected citations to the articles in table 4. We do not believe having these citations would change our conclusions.

<sup>3</sup>In 1969 several major European astronomy journals ceased

TABLE 4  
 READS IN 2000+2001 VS TOTAL CITES FOR 1950-1959 *ApJ* ARTICLES<sup>a</sup>

NC\NR	0	1	2	4	8	16	32	64	128	256	512	total
0	5.93	4.25	5.58	5.81	4.75	1.00	1.00	0.00	...	...	...	216
1	3.91	2.58	3.70	5.17	5.09	2.81	...	...	...	...	...	111
2	4.32	3.70	4.86	5.83	5.83	4.32	1.58	...	...	...	...	199
4	3.70	3.32	4.64	6.61	6.58	5.52	1.58	0.00	...	...	...	292
8	2.81	3.00	3.00	6.36	6.88	6.04	3.58	0.00	...	...	...	302
16	...	...	2.32	5.09	6.34	6.44	4.39	2.32	...	...	...	233
32	...	...	0.00	0.00	5.09	6.04	4.75	4.00	0.00	...	...	146
64	...	...	...	...	2.00	4.09	4.81	4.32	2.81	...	...	76
128	...	...	...	...	...	0.00	3.00	3.17	3.17	0.00	...	28
256	...	...	...	...	...	...	...	1.58	1.00	1.58	...	8
512	...	...	...	...	...	...	...	...	...	...	1.00	2
1024	...	...	...	...	...	...	...	...	...	...	0.00	1
total	116	56	129	364	451	312	104	56	19	4	3	1614

<sup>a</sup>In terms of the base 2 logarithm of the cross-tab counts.

publication date of the *Astrophysical Journal* article read and the time lag after the reference list was accessed, we can estimate the fraction of articles which were read by directly clicking on a reference link in the back of another article.

For articles less than one year old, this fraction is very near zero, as there has not been time for recently published papers to be referenced; this fraction slowly increases to about 1% for papers ten years old, 2% for papers twenty years old and 3% for papers thirty or more years old. For papers published in the *Astrophysical Journal* between 1950 and 1959 only about 3% of total reads are directly caused by their being cited in on-line reference lists.

Another possibility is that substantial readership of the older literature comes from non-journal based outside links. This is, in fact, true for the second most read article in table 3, Allen et al. (1995), which is pointed to by a number of educational web sites, following its appearance in the NASA Astronomy Picture of the Day web site on 1 November 1997 (NASA-APOD 1997).

To check if this practice is widespread among the older material we take the three most cited and most read papers from the 1950's *Astrophys-*

*ical Journal*, Salpeter (1955), Johnson & Morgan (1953), Abell (1958) and examine the details of their use during the month of September, 2001 using the raw web server logs. These three articles are among the most famous papers in the history of astronomy. If articles are being accessed routinely from outside educational web sites, these articles would be among those so accessed.

We found no indication that outside links play a large role in the use of these articles; two reads of Johnson & Morgan (1953) came from a static link in a Taiwanese web site, and a couple of reads of Abell (1958) came from the NED database (Helou et al. 1995) and another couple from the SIMBAD database (Wenger et al. 2000). The overwhelming majority of reads of these papers came from queries using the ADS system.

In addition to the three very well cited papers we also examined the details of the query types (from the web server logs) for all *Astrophysical Journal* articles published during the 1950's and read during the first ten days of September, 2001. We find the distribution of queries to be consistent with the distribution for the whole database (Eichhorn et al. 2000) with only one clear difference. The number of queries which have a restric-

tive date range is higher; typical is a query with an author name and an exact year. These exact queries more commonly retrieve highly cited papers than less well cited ones.

## 7. Measuring individual research productivity using reads and cites

As was demonstrated in section 6, reads and cites have substantially different properties, but fundamentally measure the same thing, the usefulness of an article. In this section we discuss some of the issues involved in combining measures of cites and reads to assess the scientific productivity of individuals. The possibility that combining information from the access logs of an electronic library with citation information could result in improved productivity measures has been noted before, notably by Kaplan and Nelson (2000).

### 7.1. Joint properties of cites and reads for individuals

To show some of the basic properties of measuring both cites and reads for individuals we use a data-set designed to show the breadth of authors of astronomy research papers; we include old/young, active/inactive, tenured/nontenured, ... individuals in the sample. For each individual we obtain from the ADS databases a list of all his/her papers published before May 2000 and for each of these papers a list of the total number of citations up to May 2000, and a list of the total number of reads in the period between January 1999 and May 2000.

The sample contains 441 individuals whose primary employment is/was in the field of astronomy. 130 of these are members of the astronomy departments of five prominent universities: Princeton, CalTech, University of California at Berkeley, University of California at Santa Cruz, and Cornell. 166 individuals are employed at the Harvard-Smithsonian Center for Astrophysics, including most of the long-term researchers plus everyone listed in the Center's phone book with a Dr. title and whose family name begins with the letters A–G. 53 individuals are winners of the Russell Prize, the highest award of the American Astronomical Society (many of these individuals are deceased, some for more than 40 years). Finally, 92 individuals are all persons who received their PhD in

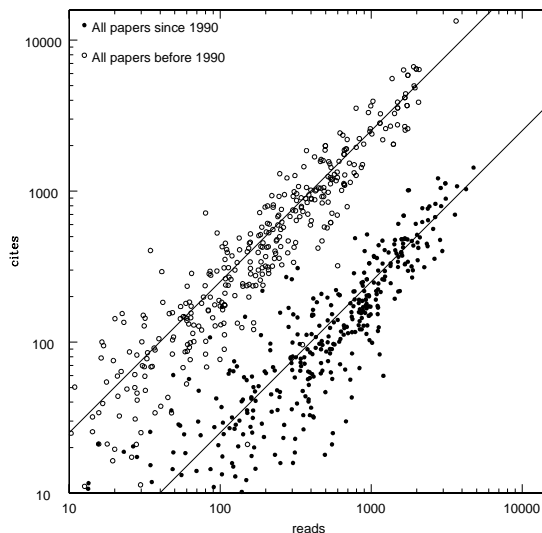


Fig. 12.— Reads vs Cites for individuals in the sample described in the text. Open circles are for papers more than ten years old and filled circles are for papers less than ten years old. The lines show linear relations, with the two relations separated by a factor of ten.

astronomy from a U.S. university during the year 1980, and have published at least one paper in the ADS database since 1990; slightly fewer than half of the persons receiving U.S. PhDs in 1980 are on the list.

#### 7.1.1. The read-cite diagram

Figure 12 shows total cites vs reads for authors from the sample. Each point represents the sum of papers written by a single individual; the open circles for papers published before 1990 and the filled circles for papers written after 1990. Once papers are separated by date the relationship between reads and cites for papers summed over single authors appears quite linear, in agreement with equation 6. The factor of ten difference between the two age groups is fully consistent with that expected using equation 4.

It is obvious from figure 12 that the position of a document in a read-cite diagram is strongly dependent on the age of the document; likewise the position of the sum of an individual author's papers in a read-cite diagram will be strongly in-

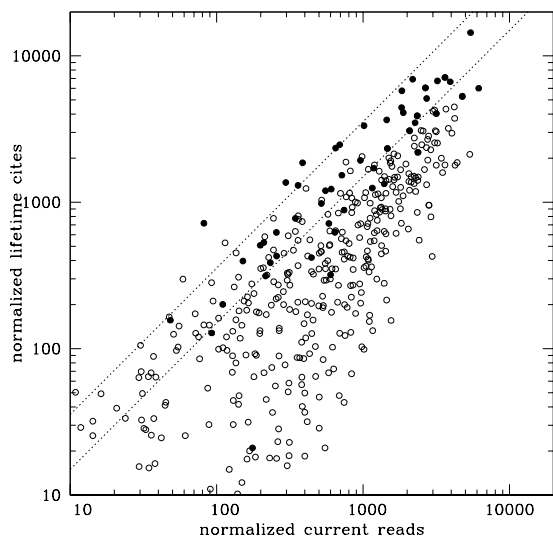


Fig. 13.— Cites vs Reads for individuals in the total sample described in the text. Filled circles are winners of the Russell Prize; open circles are the rest of the sample.

fluenced by the age of that individual.

Figures 13 and 14 show this effect. Figure 13 shows the total sample in the space of cites vs reads (with the reads and cites normalized for the number of authors on each paper), the filled circles are winners of the Russell Prize; figure 14 is the same, but here the filled squares are the 1980 PhD cohort and the crosses are persons who received their PhD after 1985. The Russell Prize winners are all substantially older than the members of the 1980 cohort; clearly the three distributions form coherent subsamples within the entire sample, and these subsamples are substantially different from each other.

The two dotted lines in figure 13 show the locus for papers which are read once every two (line on bottom-right) or five (line on top-left) years for every time they have been cited. The two dots on the five year line at about 2,500 normalized cites represent W.W. Morgan and M. Schwartzchild, two of the most distinguished astronomers of the twentieth century. Each won the Russell prize about forty years ago, and each is currently deceased. Along with table 4 this demonstrates that papers continue to be read as a function of how much they

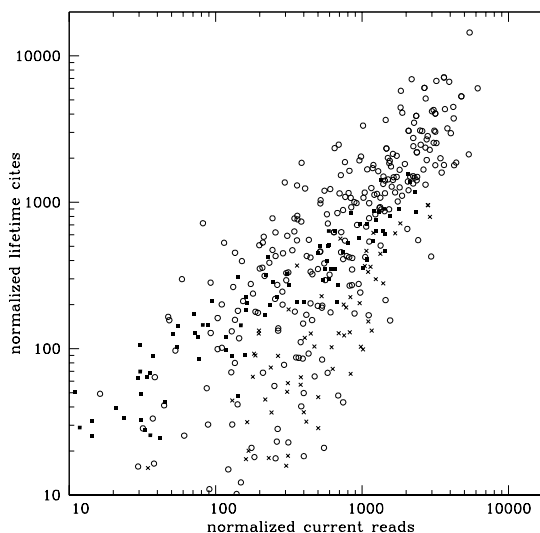


Fig. 14.— Cites vs Reads for individuals in the total sample described in the text. Filled squares are members of the 1980 PhD cohort; crosses are persons who received their PhD after 1985; open circles are the rest of the sample.

have been cited. The difference in read rates per citation between figure 13 and table 4 is due to the growth of the ADS.

Another interesting facet of figure 13 is its predictive power. Just to the right of the two year line, at about 3,000 normalized reads and 4,000 normalized cites is a group of three points, one a filled circle representing a Russell prize winner. One of the two open circles in the triplet represents W.L.W. Sargent; Professor Sargent won the Russell prize six months after this plot was made.

### 7.1.2. The age-productivity model

Using the relation between reads and cites of equation 6 and the fact that older papers are read according to how much they have been cited, we can understand these diagrams in detail. The right and top outer envelopes of figures 14 and 13 represent the most productive astronomers at different ages. The basic shape of an individual's career tract in this diagram is similar to a (somewhat tilted) figure 7, with the sharp angle appearing at the time of retirement.

A simple model which fits the data is that a

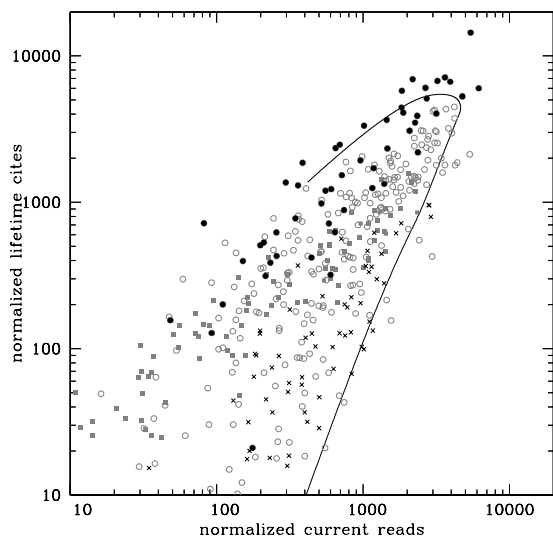


Fig. 15.— Cites vs Reads for individuals in the total sample described in the text. Filled circles are Russell prize winners; the curve represents the model for the current status of persons whose research is at the level of Russell prize winners. The gray squares represent the 1980 PhD cohort, the crosses persons who received their PhD after 1985, and circles the rest of the sample.

person starts off following the PhD being productive, this productivity grows by about a factor of two during the first seven years of one’s career and stays stable for the next twenty-three years. At thirty years past the PhD one’s productivity begins to decline until forty-two years past the PhD when one is fully retired and the number of reads declines to one per citation per couple of years.

Figure 15 shows this model for the current reads vs lifetime cites of individuals currently between one and one hundred years past the PhD. The curve bends down for individuals more than 45 years past the PhD because when they were active astronomy was a smaller field than currently, as discussed in section 6.1.2.

The fact that the large majority of Russell prize winners lie near the curve suggests that within small factors the model is an accurate representation of the productivity paths of the most productive astronomers. The tightness of the relation for Russell prize winners is underestimated in the

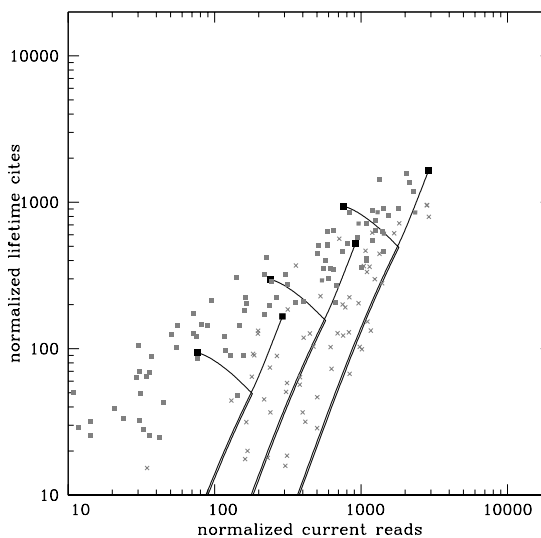


Fig. 16.— Cites vs Reads for individuals in a subset of the total sample described in the text. Filled gray squares are members of the 1980 PhD cohort; gray crosses are persons who received their PhD after 1985. The curves represent six different models for current researchers described in the text, the large dark filled squares are the different model predictions for researchers 20 years past the PhD, corresponding with the 1980 cohort.

actual data (the filled circles) due to the increasing incompleteness of the citation data base as a function of age.

Figure 16 is complex; the gray symbols are the same as in figure 15, the small gray squares are the 1980 cohort and the gray crosses are persons now working as astronomers who received their PhD after 1985. The solid lines are based on the model in figure 15. There are three groups of two models, these groups are separated from each other by equal multiplicative factors of  $\sqrt{10}$  in total productivity.

The pairs of curves at each of three productivities represent the first twenty years of two different extreme career paths for individuals. The taller of the two curves represents the same model career as the curve in figure 15, the first twenty years of the career of a person who works at his/her full capacity; the shorter curve (the one with the large "hook") represents the career of someone with ex-

actly the same latent productivity as the adjacent taller curve, but who stops performing astronomy research after ten years (perhaps leaving the field).

The six large filled black squares represent a person 20 years past the PhD (corresponding with the 1980 cohort) for each of the six models (three latent productivities, with the most productive being a factor of ten times more productive than the least productive, times two different career paths). The large black squares have essentially the same distribution as the small gray squares, thus this simple model is able to account for the distribution of the 1980 cohort in a direct way.

There are some small gray squares, those on the lower left in the diagram, which are not accounted for by the six model points. These are the least cited/read individuals. They can be accounted for either by ascribing to them a lower latent productivity, or an earlier time when they left active research. The spread in latent productivity of active researchers who got their PhDs after 1985 (the gray crosses) is about a factor of ten, and is well contained within the model lines in figure 16, thus we postulate that the natural variation of latent productivity in astronomers is about a factor of ten, and is not great enough to account for the very low cited/read individuals, thus they must have essentially left active research before ten years past the PhD. Although all in the 1980 cohort were chosen to have been co-author on at least one article of any kind since 1990 (which would be ten years past the PhD) examination of the publication records of the least cited/read confirms that they effectively stopped doing research before then.

### 7.1.3. Discussion

The read-cite diagram is a powerful new method for examining the research productivity of individuals; by comparing both measures one is able to see differences which would not be visible using either reads or cites alone. For example, if we take two hypothetical researchers, A and B, both A and B are the same age past the PhD, and both A and B have the exact same total productivity from their PhDs to now. Person A began more productive than B, and has become less productive than B over time; person B began less productive than A and has become more productive. Because citation measures more heavily weight past work,

and readership measures more heavily weight recent work person A would have more citations than person B, while person B would have more reads than person A.

Combined with the use of similar cohorts, especially same age cohorts, for comparisons, the read-cite diagram allows an individual's research to be evaluated in a manner which is more accurate and fair than is possible with the use of citation counts alone. It does not, however, provide a measure accurate enough to preclude the necessity of careful and direct examination of the record of the person being evaluated.

## 7.2. New productivity measures for individuals

It is often useful to have a single number to describe the productivity of an individual, particularly when aggregations of individuals are being studied. Citations (Garfield 1979) have served this role almost exclusively. The existence of the readership information allows other measures to be developed which in many cases are better suited to the particular study being done.

To investigate the properties of different productivity measures we have created a data-set containing the readership information for the calendar years 2000 and 2001, and the lifetime citation information for articles published before 1 January 2002 for a set of astronomers which is all tenured faculty in the ten highest rated astronomy departments in the United States (National Research Council 1995) and the federal civil servant astronomers at the Smithsonian Astrophysical Observatory, arguably the leading U.S. federal laboratory for astronomical research. For each of these 308 individuals we have also found the year their PhD was granted. We will call this data set the tenured faculty sample.

Figure 17 shows the normalized (by dividing by the number of authors for each paper) citations vs PhD date for individuals in the tenured faculty sample. The solid line represents the citation component of the individual productivity model discussed in section 7.1.2, it seems to match the outer envelope of the data quite well.

Figure 17 shows clearly the most important drawback of using citations as a productivity measure: they are very strongly biased towards older

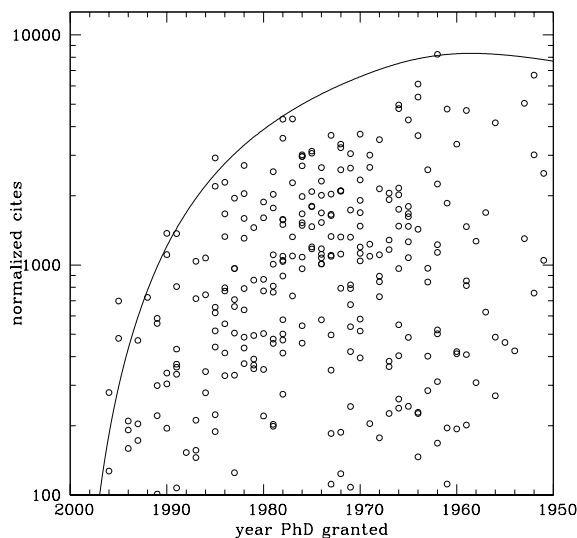


Fig. 17.— Total normalized cites for tenured faculty from the leading astronomical organizations vs. the year each person received his/her PhD. The solid line is the cites model described in the text.

individuals. Of the top ten astronomers in figure 17, one received his PhD in the 1940s, three in the 1950s, and six in the 1960s. Using the solid line as a line of constant ability shows that a person twenty years past the PhD (*i.e.* at peak productivity) will only have half the citations of a similar individual forty years past the PhD, (*i.e.* at retirement).

Another measure of productivity is the rate at which an individual's papers are being read. Figure 18 shows the normalized read rate (for the two year period) for members of the tenured faculty sample vs. PhD date. The solid line represents the readership component of the model in section 7.1.2.

Compared to the citation information the reads are much less biased as a function of age. They are, however, still biased, but toward younger individuals. Of the top ten astronomers in figure 18 one received his PhD in the 1960s, three in the 1970s, four in the 1980s, and two in the 1990s. Only one person (J.P. Ostriker) is in both lists.

Just as citations have been used with great profit in a large number of studies, the reader-

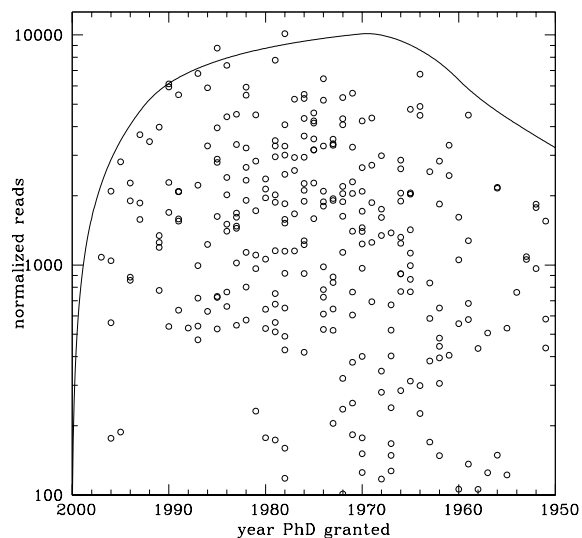


Fig. 18.— Total normalized reads in 2000 and 2001 for tenured faculty from the leading astronomical institutions vs. the year each person received his/her PhD. The solid line is the reads model described in the text.

ship information, which is a more direct measure of current usefulness, seems also well suited for use in bibliometric studies.

### 7.2.1. The *SumProd* statistic

While the direct use of the readership information may eliminate much of the age bias inherent in citation analysis it introduces other difficulties. As can be seen in figure 8 and in equation 4 the readership of an article declines very rapidly following its publication. Thus, for example, since individuals tend to have not more than a few very highly read/cited papers in their careers, the read statistic will be substantially elevated if the sample period coincides with the release of such a paper compared to a few years before or later. Citations are much more stable to these influences.

It seems justified to create a statistic which has the attributes of both the reads and the cites. We make one by adding the scaled reads to the cites, and name the statistic *SumProd*.  $SumProd \equiv (f \cdot reads + cites)/2$ , where the reads and cites are normalized by the number of authors in each paper, and the reads are multiplied by the factor  $f$

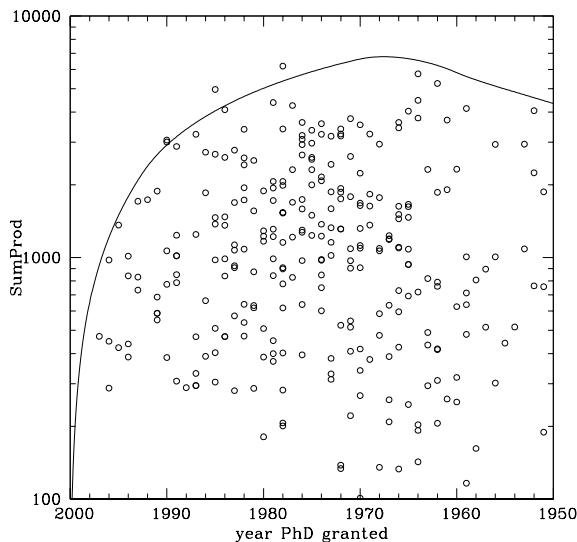


Fig. 19.— The SumProd statistic for tenured faculty from the leading astronomical institutions vs. the year each person received his/her PhD. The solid line is the productivity model described in the text.

to make the numerical weight of the current readership rate equal to the lifetime sum of the cites, over the entire sample. Dividing by two makes the numerical range the same as for citations. Figure 19 shows this statistic for the tenured faculty sample; the solid line is derived from the sum of the reads and cites lines in figures 17 and 18. The scaling factor for the reads was 0.8.

Because SumProd uses two measures with substantially different age dependencies, it is substantially more stable for younger scientists than citation counts, and it is also more stable for older scientists than the readership rate.

Of the top ten astronomers in figure 19 two received their PhDs in the 1950s, three in the 1960s, three in the 1970s, and two in the 1980s. SumProd has substantially less age bias than citation counts alone; for nearly all studies where citation counts are an appropriate measure, we suggest that SumProd would be a more appropriate measure.

For studies where age bias must be minimized, one can perform a model dependent age normalization of the data, by dividing by a model of

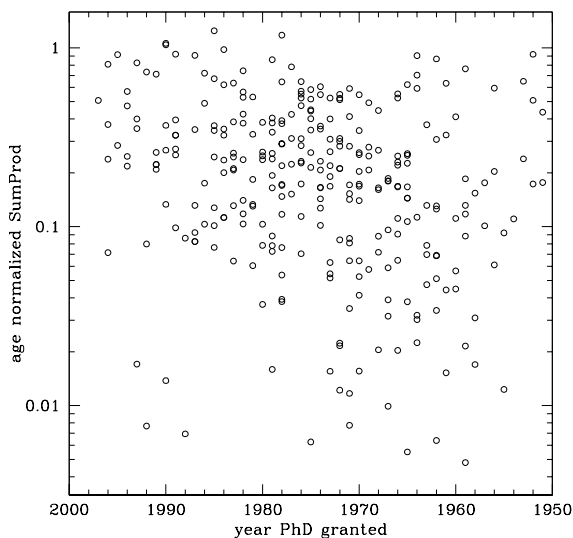


Fig. 20.— The age normalized SumProd statistic for tenured faculty from the leading astronomical institutions vs. the year each person received his/her PhD.

productivity vs age, such as shown in figures 17, 18, and 19. Figure 20 shows the SumProd statistic from figure 19 divided by the age-productivity model in that figure, that is, the age normalized relative productivities of the members of the tenured faculty sample.

### 7.2.2. The Read10 statistic

SumProd is intended to measure an individual's lifetime scientific production, where for individual's who are still active, this involves an extrapolation of their current status. Once an individual has written a paper, SumProd counts the total citations and current reads; it is not a measure of current activity. Indeed an individual's SumProd measure remains nearly constant in perpetuity. For example, W.W. Morgan would rank in the top quarter of the tenured faculty sample according to SumProd. Professor Morgan wrote his last scientific paper about twenty years ago, and died in 1994.

We create the Read10 statistic to measure the current activity of individuals. Read10 is the current readership rate for all an individual's papers published in the most recent ten years, normalized



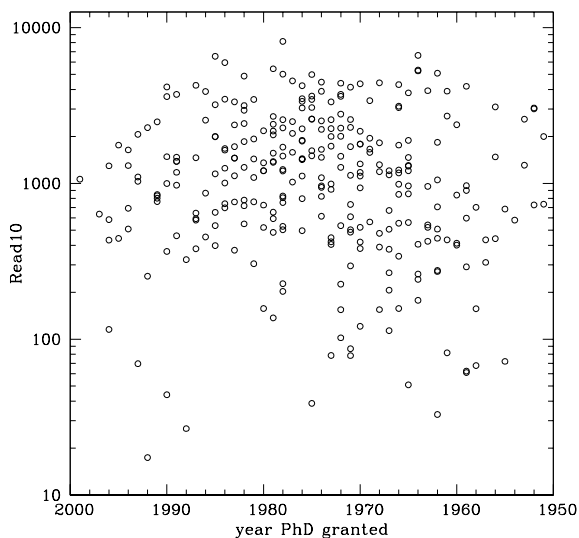


Fig. 21.— The Read10 statistic for tenured faculty from the leading astronomical institutions vs. the year each person received his/her PhD.

for number of authors. Figure 21 shows the distribution of Read10 as a function of an individual's age. The only obvious age bias is for researchers who have not yet been in the field ten years.

For persons in the first ten years of their careers Read10 is exactly the same as the normal readership measure of figure 18. Read10 is very sensitive to changes in output; if one stops publishing Read10 will drop to half its value in about three years, and drop to zero in ten years.

Read10 vs age diagrams, such as figure 21, can provide a powerful means of analyzing the staffing practices of an organization over time. It is sometimes alleged that in some places professors essentially “retire” from research following tenure; this effect would be immediately obvious in these diagrams.

### 7.3. The effect of normalization

All the statistical measures developed in this section have used readership and citation measures which have been normalized to account for the number of authors of each paper. This assumes that each author bears equal responsibility in the creation of a paper.

This assumption is least accurate when applied

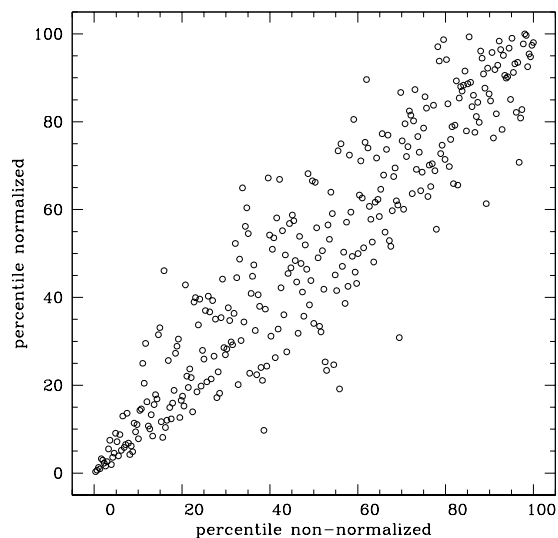


Fig. 22.— The percentile rank of members of the tenured faculty sample obtained by using a version of the SumProd statistic which has not been normalized for number of authors vs. their percentile rank obtained using the ordinary (normalized) SumProd.

to a single paper; it becomes more accurate when applied to all the papers of an individual author, as is done in all the plots in this section, and becomes a quite reasonable assumption when applied to groups of individuals.

The alternative measure, ascribing the total reads and/or citations for each paper to each author is clearly not viable for studies of groups of individuals, as the importance of a citation or read would depend on the number of authors of a particular paper who are members of a particular group.

Certainly many analyses of citation counts for individuals are performed with the raw (not normalized by number of authors) counts. These studies can often come to different conclusions than studies using normalized counts would; Herstein (1993) has argued that the normalized counts are more accurate. These differences are becoming more pronounced as the number of authors per papers increases, (e.g. Schulman et al. (1997)), and especially due to the trend to have papers with very long author lists.

Figure 22 shows this effect for members of the tenured faculty sample. We created a non-normalized analog of SumProd and sorted the list of people by their non-normalized score. This we compared with their rank using the ordinary, normalized SumProd. The ranks are scaled into percentiles, 0–100. While there is a basic trend, that a person who is low/high in one statistic will be low/high in the other, there is a large scatter. It is equally likely that a person at the median of one statistic will be anywhere from the 30th to the 70th percentile of the other. There is an individual who is in the 97th percentile using the non-normalized statistic who is only at the 70th percentile using the normalized statistic. None of the top five individuals in one statistic overlap with the top five in the other.

## 8. Measuring the prestige and productivity of research organizations

Bibliographic measures of scientific productivity have long been tools to assess various aspects of an organization's stature, progress, and desirability. Ranking similar research organizations relative to each other, either by reputations (e.g. National Research Council (1995), hereafter NRC95) or using bibliographic measures, is often used as a tool in determining public policy.

Additionally bibliometric measures are often used by internal review committees to assess the personnel policy of an organization or department.

In this section we develop techniques to analyze the performance of groups of individuals, using the bibliometric measures developed in the previous section.

### 8.1. Productivity–Percentile Diagrams

Given a productivity measure or score for individuals, whether SumProd, Read10, number of citations, or some other, how can one compare groups of individuals, such as university departments? Traditional methods are to use the sum or average of the individual scores. Because of the logarithmic nature of these measures this is not a satisfactory technique; for example Alan Sandage, the most cited living astronomer, has a normalized citation score about twenty times the median score for the tenured faculty sample. As a large astronomy department faculty has about twenty

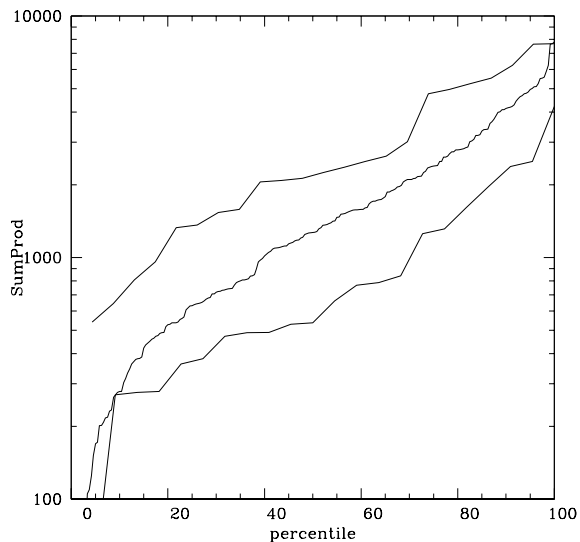


Fig. 23.— The percentile rank of members of the ten faculty sample using the SumProd statistic (thick line) and for members of the Princeton (top thin line) and Cornell (bottom thin line) faculties.

members, it is obvious that one or two very high scoring individuals would skew any sum or average.

We develop a technique which compares the distribution of rank ordered individual scores for an entire faculty with the distribution of rank ordered scores for members of several faculties together; figure 23 illustrates the technique.

To compare the top astronomy departments in the U.S., we create a sample which is comprised of the 240 tenured faculty of the top ten astronomy departments according to NRC95, this sample (which we name the ten faculty sample) is the same as the tenured faculty sample of section 7.2, but with the Smithsonian federal employees removed. We then rank order all these individuals, and scale their ranks onto a 0–100 percentile scale. The thick line in figure 23 shows this distribution, using SumProd as the measure.

To compare an organization with the ten faculty sample, we make the same score-percentile distribution for the persons within that organization. The thin lines above and below the thick line in figure 23 show this distribution for the Princeton and Cornell faculties. Next we (numerically)

shift the score-percentile distribution for the reference sample up or down to achieve the best fit to the distribution for the organization being compared. As this is a log plot, this is equivalent to multiplying the productivity score of each person in an organization by a constant factor to equal the productivity of the reference sample at that person's percentile rank, and taking the average factor for all individuals in the organization as the result. We only use individuals above the 20th percentile in their organizations in order to minimize the effect of the lowest performers.

The multiplicative factor for Princeton in figure 23 is 1.70 and for Cornell is 0.52. Table 5 shows the scores and rankings for the top 11 organizations as ranked by NRC95, based on perceptions of faculty quality. Both SumProd and Read10 scores and rankings are shown, along with the NRC95 ranking. By construction the ten faculty sample has a multiplicative factor of 1.00 (to match itself).

The members of each faculty were simply taken from each department's web page, taking the professors and associate professors, with two exceptions. M.I.T. does not have an astronomy department, we used the faculty (from four departments) associated with the Center for Space Research. The NRC95 study ranked Harvard, however Harvard is a part of the Harvard-Smithsonian Center for Astrophysics, and it is essentially impossible to separate the organizations from the outside. We have taken as a sample closest to an academic department the persons listed as professors or lecturers on the Harvard web page, 75% of these individuals are Smithsonian federal scientists.

All three rankings are similar; in particular the top four institutions are the same in each ranking, with Princeton, CalTech, and Harvard-Smithsonian each getting one 1st ranking, and U.C. Berkeley being third in all three measures. The only important difference between the SumProd and Read10 rankings and the NRC95 ranking is that the U. Hawaii is higher in both SumProd and Read10, and the U. Chicago is lower.

The NRC95 study ranked more than two dozen astronomy faculties, some of these would doubtless have Read10 or SumProd scores higher than some of the eleven in table 5. The University of Minnesota, for example was ranked 24th by NRC95, but would be ranked eighth by either SumProd or

Read10. U. Minnesota has a distribution which is substantially flatter than the reference distribution, and is between one half and one third the size of the eleven organizations ranked. A complete analysis of the astronomy departments in the United States is beyond the scope of this article.

The productivity percentile method measures a type of average productivity for an entire faculty; it is sensitive to the exact composition of the membership of the organizations being ranked. In table 5 we have attempted to keep the samples uniform, by restricting the membership to tenured professors. Much astronomy research in the United States is performed in government supported laboratories, and the employees of these organizations cannot directly be compared with the all faculty sample.

Perhaps the two largest federally supported organizations which perform astronomical research in the U.S. are the Smithsonian Astrophysical Observatory and the Goddard Space Flight Center, which has two laboratories for astronomy: The Laboratory for High Energy Astrophysics, and The Laboratory for Astronomy and Solar Physics. The number of federal civil servant scientists (the closest approximation to academic researchers) at SAO is 64, about two or three times as large as the astronomy departments in table 5, the number of civil servant scientists in the combined labs at Goddard is 100.

If we compare these two organizations directly against the ten faculty sample, as with the departments in table 5, SAO would have a score of 0.80 in SumProd (which would rank 7th) and 0.92 in Read10 (ranking 5th). Goddard would have scores of 0.27 in SumProd and 0.34 in Read10.

As federal civil service scientists can be at any level of seniority, and can be persons who would be viewed as technicians in academic departments, there is a bias in including these individuals in samples intended to measure the quality of publishing scientists. One way to compensate for this is to take a subset for the comparison. If we take the top half (probably too large a correction) we get SAO with a SumProd score of 1.44 (ranking 3rd) and a Read10 score of 1.69 (ranking 1st); Goddard would have 0.51 for SumProd (ranking 11th) and 0.73 for Read10 (ranking 8th). A more detailed analysis is beyond the scope of this paper.

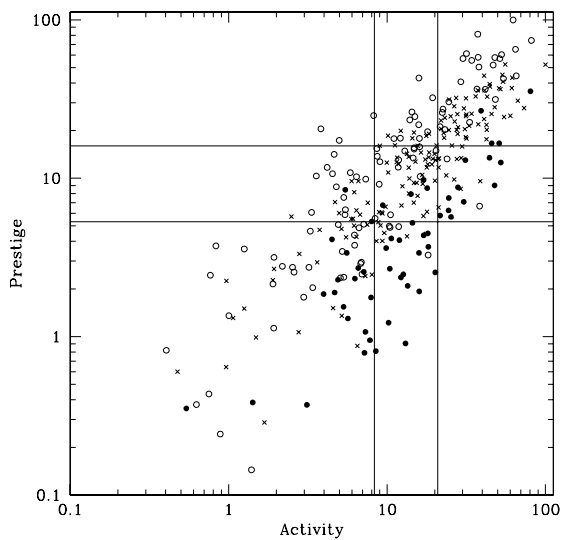


Fig. 24.— The score in percent of the maximum score of members of the tenured faculty sample using the normalized citation statistic (Prestige) vs. their score in percent of maximum using the Read10 (Activity) statistic. Circles are for PhD year before 1970, crosses between 1970 and 1985, and dots after 1985. The lines divide the sample into equal thirds.

With the productivity-percentile method of this section we have shown how to compare the average productivity of organizations independent of size, and we have indicated how to use these methods taking organization size and composition into account (by taking a fixed number of individuals or a subset of individuals for the representative sample).

## 8.2. Productivity–Productivity Diagrams

The Read-Cite diagrams of section 7 can obviously be used to compare groups of individuals simply by plotting the members of two organizations and comparing their positions in detail. To emphasize this point, we present another, similar diagram in figure 24.

Figure 24 shows citations vs Read10 for the tenured faculty sample, with the points crudely representing age, as noted in the caption. We have relabeled Read10 as Activity and (normalized) citations as Prestige to emphasize the expected use

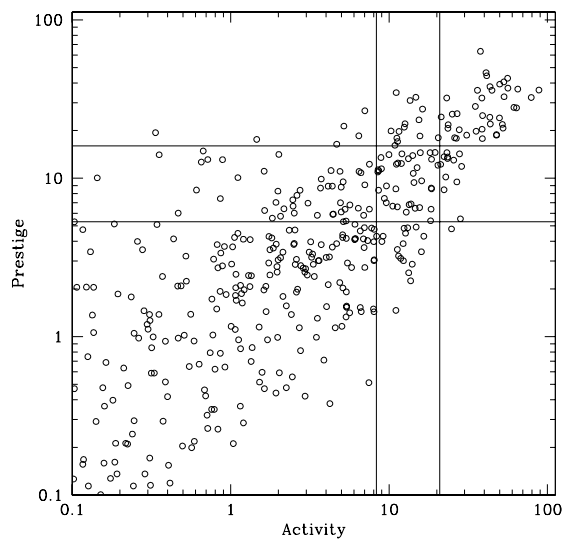


Fig. 25.— The Activity-Prestige diagram for all 928 individuals who received a PhD from a U.S. university in the five year period 1972-1976. The scaling of the axes and the horizontal and vertical lines are the same as in figure 24.

of this diagram. We have divided the tenured faculty sample in thirds, both by Read10 and citations, this is shown in the divisions in the diagram, persons with high activity and high prestige are in the top right of the diagram, for example.

Clearly the distributions of different groups in diagrams such as figure 24 can be analyzed and compared in a number of ways. As an example we show in figure 25 all 928 persons who received their PhDs from a U.S. university in the five year period 1972-1976, plotted on the same scale as in figure 24. As expected there are substantial differences between the age cohort and the faculties of the most prestigious organizations. The high activity–high prestige corner contains 26% of the faculty sample, but only 4% of the age cohort, and the low activity–low prestige corner contains 24% of the faculty sample but 80% of the age cohort.

## 8.3. Integrated Productivity–Productivity Diagrams

The methods in section 8.1 measure the average quality of organizations independent of size; but in frequent cases size matters. A good measure of the

TABLE 5  
ASTRONOMY FACULTY RANK

Institution	SumProd Rank	SumProd Score	Read10 Rank	Read10 Score	NRC Rank <sup>a</sup>
Princeton	1	1.70	2	1.52	2
CalTech	2	1.46	4	1.28	1
U.C. Berkeley	3	1.32	3	1.44	3
Harvard-Smithsonian	4	1.21	1	1.60	4
U.C. Santa Cruz	5	.83	7	.82	6
U. Hawaii	6	.82	5	.87	11
U. Arizona	7	.78	6	.85	7
U. Texas	8	.71	8	.49	10
U. Chicago	9	.57	11	.39	5
Cornell	10	.52	10	.45	9
M.I.T.	11	.46	9	.47	8

<sup>a</sup>By perception of faculty quality (National Research Council 1995)

product of size and ability for an organization is the number of high ranking scientists in that organization. We choose to define high ranking as having a score which would be in the top third of the ten highest ranked faculties in the U.S., and we count these individuals using the activity and prestige measures Read10 and normalized citations.

Figure 26 shows the results for the eleven faculties ranked in table 5. The effect of size can be seen in the measures for U.C. Berkeley and U.C. Santa Cruz; they have exactly the same score (the symbols are offset on the plot for legibility) of 10 highly active and 9 highly prestigious people. As can be seen in table 5, the Berkeley department is ranked about 50% above the Santa Cruz department by faculty quality, U.C. Santa Cruz is about 50% larger than U.C. Berkeley, thus in this figure they are equal. The small, high quality department at U. Minnesota has an (active, prestigious) score of (2,3) which would rank it below a number of larger departments.

It is also possible to measure the federal labs on the same scale as the universities using this method. The federal civil service scientists at the Smithsonian Astrophysical Observatory would have an (active, prestigious) score of (18,16), above any university in both measures, and the combined astrophysics labs at the Goddard Space

Flight Center would have a score of (10,2).

## 9. The impact of the ADS and the electronic astronomy library

The ability to access information rapidly and easily is transforming modern civilization. Many have compared the recent advances in electronic communications with the invention of the printing press in terms of historical importance. The widespread use of the ADS has clearly had a profound effect on how astronomical research is performed; in this section we attempt to quantify the magnitude of that effect.

Expanding on the discussion in Kurtz et al. (2000), we define the concept of utility time as a measure of how a tool improves efficiency. Utility time is the time which would have to have been spent to achieve the same result, were the tool not present. For a research tool such as the ADS this is the amount of research (or researcher's) time gained by using the ADS compared with not using it.

The principle "product" of the ADS is access to articles in research journals. It is difficult to determine the research time gained by reading an article in a research journal. It can range from zero (the article was worthless, so the time was

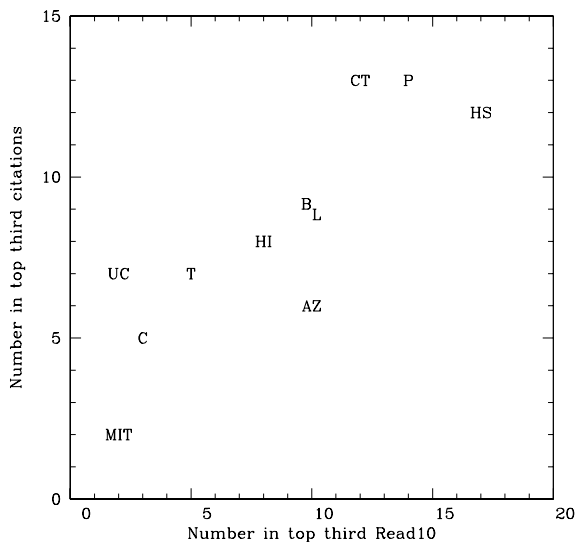


Fig. 26.— The number of faculty members from each organization who have Read10 scores in the top third of the ten faculty sample vs. the number whose citations rank in the top third. The meaning of the symbols is P: Princeton; CT: Cal-Tech; HS: Harvard-Smithsonian; B: U.C. Berkeley; L: U.C. Santa Cruz (Lick observatory); HI: U. Hawaii; AZ: U. Arizona; T: U. Texas; UC: U. Chicago; C: Cornell; MIT: M.I.T.

wasted) to years (the proposed study has already been done). On the average, however, the time gained by reading the technical literature must be positive, and at least equal to the time spent getting and reading it; otherwise rational scientists would not waste their time reading the literature.

The ADS combined with the electronic journals essentially eliminate the time required to get an article. We estimate this by timing the first author (MJK) as he writes a reference on a small piece of paper, walks two flights downstairs to the library, searches the stacks for the proper volume (it was an *Astrophysical Journal* reference), takes the volume to the photocopy machine and photocopies the article, then finally walks back upstairs to his office. 15 minutes was the elapsed time, and we take that as the utility measure in research time gained by using the ADS to obtain a full text article from the technical literature.

Obviously much of the credit for the ease of

access to the electronic literature goes to the electronic journals themselves. In astronomy the electronic journals and the ADS have grown up together in a symbiotic relationship. Here we make no attempt to split credit for what have been joint developments. Credit for the utility of the contents of the journals is a separate issue, and clearly belongs to the journals.

We also assign one third of the utility value for whole text retrieval (5 minutes) to the retrieval of an abstract, reference list, or citation list. In practice this is probably an underestimate.

Finally we arbitrarily assign a one minute benefit for each simple query made to the system. Even a very common query, such as ‘show me recent papers by author X’ would take longer than a minute to get by any pre-ADS means, while complex queries, such as the joint ADS–SIMBAD query ‘show me papers about the metallicity of the globular clusters in the galaxy M87’ would have taken from hours to weeks previously.

The result for the research time gained using the ADS during the year 2002 is shown in table 6. The table shows the types of data available via the ADS for articles, how many times each type was accessed in 2002, the utility value assigned to each type, and the total research time gained, measured in 2,000 hour full time equivalent researcher years. For a detailed description of all the various data types see Eichhorn et al. (2000). The bottom line is that the ADS improved astronomical research during 2002 by the equivalent of 736 full time researchers.

To put 736 FTE researchers into perspective: The Harvard-Smithsonian Center for Astrophysics, the largest astronomical research facility in the United States, has about 300 research scientists, and has an annual budget of about \$100 Million. If the ADS provides  $2\frac{1}{2}$  times the research scientists as the CfA its annual value to astronomy research can be calculated as  $2\frac{1}{2}$  times the CfA budget, or \$250 Million. The ADS yearly budget is but a tiny fraction of that sum.  $2\frac{1}{2}$  times the CfA is also approximately the astronomical research output of the country of France.

From another perspective we can estimate that there are ~12,000 astronomers in the world. 736 FTE astronomers would then represent ~6% of the worlds astronomers. Woltjer (1998) estimates

that the yearly budget for astronomy research, worldwide, is between \$4000 and \$5000 Million. 6% of that would be between \$240 and \$300 Million, essentially the same as in the preceding paragraph.

Another way to view the impact of the ADS and the electronic journals on astronomy research is to compare the total readership of astronomy's technical literature now with what it was previously. Kurtz et al. (2000) estimated the total number of astronomy research articles read in traditional libraries at about 600,000 per year. If one ignores articles read in the browse mode upon arrival of a new journal (the N mode of section 5.1) the number of articles read by individuals with personal subscriptions must be less than the total read in libraries. We will estimate that no more than 1.2 million papers per year are read by astronomers using non-electronic means.

Table 6 shows that 3.4 million full text articles have been accessed using the ADS during 2002, nearly three times the total number of non-electronic reads. In addition 4.2 million abstracts were accessed and 0.8 million citation and reference lists; this represents an entirely new mode of rapid information gathering on the part of researchers. The ADS and the electronic astronomical library have succeeded in increasing the total readership and use of the technical astronomical literature by a factor of at least three within a very short time; this represents a massive change in the research behavior of working astronomers today.

## 10. Conclusions

As the first digital science, astronomy has long been a leader in the information technologies which are transforming our civilization. With respect to the astronomical technical literature the close collaboration of the data centers, the journals, and the ADS has created a fully integrated system of enormous power; within just a few years it has become universally used.

At the heart of this system, the ADS presides over a huge database, with many of the data-sets being brought together for the first time. Simple queries, such as 'show me the most cited papers containing the phrase "redshift survey"' were not possible before the ADS merged the text and ci-

tation databases.

Perhaps the most important new information to become available for bibliometric studies is the per article readership information. We now know how many times an article is read, where the reader is from, and "who" (as a unique cookie identifier, not as a name, which remains anonymous) the reader is. The existence of this information has great implications for the future of information retrieval and bibliometrics.

We have demonstrated, in section 2.1, that very sophisticated and powerful retrieval algorithms can be created by merging text, citation, and reference databases with a database of articles and their readers. Surely numerous new techniques will be developed in the coming years taking advantage of the tremendous possibilities inherent in these data.

In section 4 we showed that the correlation of readership information with place can permit large scale sociometric studies of the research efforts of countries, as well as smaller entities. The ease and rapidity with which this information can be gathered will not only permit similar studies in other fields, but will also permit changes in relative activity to be studied in nearly real-time.

We expect the similarities and differences of reads and citations to become a central facet of bibliometric research. Whether emphasizing the similarities to achieve a statistically more stable result, as with our SumProd statistic, or emphasizing the differences to obtain a two dimensional view, as with the citations vs. Read10 diagram, the combination of the two measures of use substantially improves the capabilities of bibliometric measurement.

The number of research articles published in astronomy has increased by a factor of four in the time since astronomers now on the verge of retirement entered the field. For years this explosion of information has proved a problem, as researchers were able to read a smaller and smaller fraction of the published literature. With the advent of the new information technologies inherent in the electronic astronomy library, and centered about the ADS, researchers are now able to find and read a substantially larger fraction of what is published; essentially they are now able to read the same fraction as forty years ago. These technologies have

TABLE 6  
ADS USE 2002

Code	Function <sup>a</sup>	Number	Time <sup>b</sup>	Research Gain <sup>c</sup>
A	Abstract	4,171,704	5	174
C	Citations	676,305	5	28
D	Data	61,678		
E	HTML Article	864,019	15	108
F	PDF Article	1,872,035	15	234
G	GIF Article	677,821	15	85
I	Author Comments	748		
L	Library Entry	2,682		
M	Document Delivery	9,322		
N	NED Entry	33,963		
O	Associated Articles	10,373		
P	PDS Entry	76		
R	Reference List	152,188	5	6
S	SIMBAD Entry	97,691		
T	Table of Contents	47,373		
U	Also Read	150,891		
	Simple Queries	12,168,336	1	101 736

<sup>a</sup>See Eichhorn et al. (2000) for a full description

<sup>b</sup>Minutes of research time gained per query

<sup>c</sup>In 2000 hour FTE Research Years



changed, and continue to change, the practice of scientific research in a fundamental way.

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## REFERENCES

- American Astronomical Society 2001, <http://www.aas.org>.
- Abell, G. O. 1958, The Distribution of Rich Clusters of Galaxies. *ApJS*, 3, 211.
- Accomazzi, A., G. Eichhorn, M. J. Kurtz, C. S. Grant, and S. S. Murray 2000. The NASA Astrophysics Data System: Architecture. *A&AS* 143, 85-109.
- Allen, R. J., Le Bourlot, J., Lequeux, J., Pineau des Forets, G., & Roueff, E. 1995, Physical properties of molecular clouds in the inner disk of M31. *ApJ*, 444, 157.
- Amazon.com 2002, <http://www.amazon.com>
- Belkin, N.J., Kantor, P., Fox, E.A. & Shaw, J.A. 1995, Combining the Evidence of Multiple Query Representations for Information-Retrieval, *Information Processing and Management*, 31, 431.
- Bonitz, M. 1997, The Scientific Talents of Nations, *Libri*, 47, 203.
- Boyce, P. B. 1998. Urania, a Linked, Distributed Resource for Astronomy. *ASP Conf. Ser.* 153: Library and Information Services in Astronomy III, 107.
- Boyce, P. 1996. Journals, Data and Abstracts Make an Integrated Electronic Resource. *American Astronomical Society Meeting* 189, 0603.
- Boyce, P. B. 1995. The Electronic *ApJ* Letters. *American Astronomical Society Meeting* 187, 3801.
- Brunner, R. J., S. G. Djorgovski, and A. S. Szalay 2001. *Virtual Observatories of the Future*. *ASP Conf. Ser.* 225.
- Burton, R.E. and Kebler, R.W. 1960, The Half-Life of some Scientific and Technical Literatures, *American Documentation*, 11, 18.
- CIA ( U. S. Central Intelligence Agency) 2001, *CIA World Factbook*. <http://www.cia.gov/cia/publications/factbook/>
- Coletti, D.J. 1999, Report from the Librarian, Harvard-Smithsonian Center for Astrophysics, John G. Wolbach Library.
- Cooper, M.D. and McGregor, G.F. 1994, Using Article Photocopy Data in Bibliographic Models for Journal Collection Management. *Library Quarterly* 64, 386.
- Corbin, B. G. and D. J. Coletti 1995. Digitization of Historical Astronomical Literature. *Vistas in Astronomy* 39, 161-165.
- Dalterio, H. J., P. B. Boyce, C. Biemesderfer, A. Warnock, E. Owens, and J. Fullton 1995. The Electronic Astrophysical Journal Letters Project. *Vistas in Astronomy* 39, 7-12.
- Demleitner, M., A. Accomazzi, G. Eichhorn, C. S. Grant, M. J. Kurtz, and S. S. Murray 1999. Looking at 3,000,000 References Without Growing Grey Hair. *American Astronomical Society Meeting* 195, 8209.
- Dewan, S. and Kraemer, K.L. 2000, *Management Science* 46, 548.
- Egghe, L. 1993, On the Influence of Growth on Obsolescence, *Scientometrics* 27, 195.
- Eichhorn, G., M. J. Kurtz, A. Accomazzi, C. S. Grant, and S. S. Murray 2000. The NASA Astrophysics Data System: The search engine and its user interface. *A&AS* 143, 61-83.

- Eichhorn, G., A. Accomazzi, C. S. Grant, M. J. Kurtz, S. S. Murray, D. Egret, F. Genova, S. Lesteven, and M. Wenger 1996. It's All Done With Mirrors: Improving Information Access. American Astronomical Society Meeting 189, 0601.
- The Economist Magazine 2001, Country Briefings, <http://www.economist.com/countries/>
- Garfield, E. 1979, Citation Indexing: Its Theory and Application in Science, Technology, and Humanities, New York: Wiley.
- Genova, F., D. Egret, O. Bienaymé, F. Bonnarel, P. Dubois, P. Fernique, G. Jasniewicz, S. Lesteven, R. Monier, F. Ochsenbein, and M. Wenger 2000. The CDS information hub. On-line services and links at the Centre de Données astronomiques de Strasbourg. *A&AS* 143, 1.
- Goldberg, D., Nichols, D., Oki, B.M., and Terry, D., 1992 Using Collaborative Filtering to Weave an Information Tapestry, *Communications of the ACM* 35 (12), 61.
- Grant, C. S., A. Accomazzi, G. Eichhorn, M. J. Kurtz, and S. S. Murray 2000. The NASA Astrophysics Data System: Data holdings. *A&AS* 143, 111-135.
- Grant, C. S., M. J. Kurtz, and G. Eichhorn 1994. The ADS Abstract Service: One Year Old. American Astronomical Society Meeting 184, 2802.
- Helou, G., Madore, B. F., Schmitz, M., Wu, X., Corwin, H. G., Lague, C., Bennett, J., & Sun, H. 1995, The NASA/IPAC Extragalactic Database, *ASSL Vol. 203: Information & On-Line Data in Astronomy*, 95.
- Herbstein, F.H. 1993, Measuring Publications Output and Publications Impact of Faculty Members of a University Chemistry Department. *Scientometrics* 28, 349.
- Highwire Press (Stanford University), 2001, <http://highwire.stanford.edu/lists/largest.dtl>
- International Astronomical Union 2001, Membership Statistics as of March 28, 2001. *IAU Information Bulletin* 89, 32.
- Institute for Scientific Information 2002, Web of Science, <http://www.isinet.com>.
- Johnson, H. L. & Morgan, W. W. 1953, Fundamental stellar photometry for standards of spectral type on the revised system of the Yerkes spectral atlas. *ApJ*, 117, 313.
- Kaplan, N.R. and Nelson, M.L. 2000, Determining the Publication Impact of a Digital Library. *Journal of the American Society for Information Science*, 51, 324.
- Kurtz, M. J. 1992. Second Order Knowledge: Information Retrieval in the Terabyte ERA. *Astronomy from Large Databases II*, 85.
- Kurtz, M. J. and G. Eichhorn 2001. Evolution of Urania into the AVO. *Proc. SPIE* 4477, 186-190.
- Kurtz, M. J., Eichhorn, G., Accomazzi, A., Grant, C. S., Rey Bacaicoa, v., and S. S. Murray. 2002, Second Order Bibliometric Operators in the Astrophysics Data System. *Proc. SPIE* 4847, 238.
- Kurtz, M. J., G. Eichhorn, A. Accomazzi, C. S. Grant, S. S. Murray, and J. M. Watson 2000. The NASA Astrophysics Data System: Overview. *A&AS* 143, 41-59.
- Kurtz, M. J., Eichhorn, G., Accomazzi, A., Grant, C. S., Demleitner, M., & Murray, S. S. 1999, *D-Lib Magazine*, 5, (on-line only).
- Kurtz, M. J., G. Eichhorn, A. Accomazzi, C. S. Grant, and S. S. Murray 1996. Journal Citations: An ADS-AAS Collaboration. American Astronomical Society Meeting 189, 0607.
- Kurtz, M. J., T. Karakashian, C. S. Grant, G. Eichhorn, S. S. Murray, J. M. Watson, P. G. Ossorio, and J. L. Stoner 1993. Intelligent Text Retrieval in the NASA Astrophysics Data System. *ASP Conf. Ser. 52: Astronomical Data Analysis Software and Systems II*, 132.
- Landolt, A. U. 1992. UBVR photometric standard stars in the magnitude range 11.5-16.0 around the celestial equator. *AJ* 104, 340-371.
- Liu, M. 1993, Progress in Documentation The Complexities of Citation Practice: A Review of Citation Studies. *Journal of Documentation* 49, 340.

- Line, M.B. 1993, Changes in the Use of Literature with Time—Obsolescence Revisited, *Library Trends*, 41, 665.
- Line, M.B. and Sandison, A. 1975, Progress in Documentation - Obsolescence and Changes in Use of Literature with Time, *Journal of Documentation* 30, 283.
- MacRoberts, M.H. and MacRoberts, B.R. 1989, Problems in Citation Analysis, *Journal of the American Society for Information Science*, 40, 342.
- Merton, R.K. 1968, The Matthew Effect in Science, *Science*, 159, 56.
- Moya-Anegón, F. de and Herrero-Solana, V. 1999, Science in Latin America: A Comparison of Bibliometric and Scientific-Technical Indicators. *Scientometrics* 46, 299.
- Murray, S. S., E. W. Brugel, G. Eichhorn, A. Farris, J. C. Good, M. J. Kurtz, J. A. Nousek, and J. L. Stoner 1992. The NASA Astrophysics Data System: A Heterogeneous Distributed Processing System Application. *Astronomy from Large Databases II*, 387.
- NASA 1997, APOD: November 1, 1997 - M31: The Andromeda Galaxy, <http://antwrp.gsfc.nasa.gov/apod/ap971101.html>
- National Research Council 1995, *Research-Doctorate Programs in the United States: Continuity and Change*. (Washington, D.C.: National Academy Press).
- Ochsenbein, F. and J. Lequeux 1995. The A&A Tables and Abstracts: an Example of Collaboration Between Data Centres and Editors. *Vistas in Astronomy* 39, 227-233.
- Phelan, T.J. 1999, A Compendium of Issues for Citation Analysis, *Scientometrics*, 45, 117.
- Plante, R. L., R. M. Crutcher, and R. K. Sharpe 1996. The NCSA Astronomy Digital Image Library. ASP Conf. Ser. 101: *Astronomical Data Analysis Software and Systems V*, 581.
- Price, D.J. de Solla 1965, Networks of Scientific Papers, *Science*, 149, 510.
- Riess, A. G., A. V. Filippenko, P. Challis, A. Clocchiatti, A. Diercks, P. M. Garnavich, R. L. Gilliland, C. J. Hogan, S. Jha, R. P. Kirshner, B. Leibundgut, M. M. Phillips, D. Reiss, B. P. Schmidt, R. A. Schommer, R. C. Smith, J. Spyromilio, C. Stubbs, N. B. Suntzeff, and J. Tonry 1998. Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant. *AJ*, 116, 1009-1038.
- Salpeter, E. E. 1955, The Luminosity Function and Stellar Evolution. *ApJ*, 121, 161.
- Sandison, A. 1971, The Use of Older Literature and its Obsolescence, *Journal of Documentation* 27, 184.
- Satariano, W.A. 1978, Journal Use in Sociology: Citation Analysis versus Readership Patterns. *Library Quarterly* 48, 293.
- Schulman, E., French, J. C., Powell, A. L., Eichhorn, G., Kurtz, M. J., & Murray, S. S. 1997, Trends in Astronomical Publication Between 1975 and 1996, *PASP*, 109, 1278.
- Seglen, P. O. 1997, Citations and Journal Impact Factors: Questionable Indicators of Research Quality. *Allergy* 52, 1050.
- Small, H.G. 1987, The Significance of Bibliographic References, *Scientometrics*, 12, 339.
- Tenopir, C., King, D.W., Boyce, P., Grayson, M., and Paulson, K.-L. 2003. Relying on Electronic Journals: Reading Patterns of Astronomers, *JASIST*, submitted.
- Trimble, V. and M. J. Aschwanden 2002. Astrophysics in 2001. *PASP*, 114, 475-528.
- Trimble, V. and M. J. Aschwanden 2001. Astrophysics in 2000. *PASP*, 113, 1025-1114.
- Trimble, V. and M. J. Aschwanden 2000. Astrophysics in 1999. *PASP*, 112, 434-503.
- Trimble, V. and M. Aschwanden 1999. Astrophysics in 1998. *PASP*, 111, 385-437.
- Tsay M.-Y. 1998, Library Journal Use and Citation Half-Life in Medical Science. *Journal of the American Society for Information Science* 49, 1283.

Wenger, M., F. Ochsenbein, D. Egret, P. Dubois, F. Bonnarel, S. Borde, F. Genova, G. Jasniewicz, S. Laloe, S. Lesteven, and R. Monier 2000. The SIMBAD astronomical database. The CDS reference database for astronomical objects. *A&AS* 143, 9-22.

Wente, V.A. 1990, Scientific and technical information management, *Government Information Quarterly*, 7, 149.

White, H.D. 2001, Authors as Citers over Time. *Journal of the American Society for Information Science*, 52, 87.

White, H.D. and McCain, K.W. 1989, Bibliometrics, *Annual Review of Information Science and Technology*, 24, 119.

Woltjer, L. 1998, Economic Consequences of the Deterioration of the Astronomical Environment. *ASP Conference Series* 139, Preserving the Astronomical Windows. 243.