Abstract

We have used data from the Astrophysics Data System (ADS), the American Astronomical Society (AAS), and the arXive electronic preprint server (astro-ph), to study the publishing, preprint posting, and citation patterns for papers published in The Astrophysical Journal (ApJ) in 1999 and 2002. This allowed us to track statistical trends in author demographics, preprint posting habits, and citation rates for ApJ papers as a whole and across various subgroups and types of ApJ papers. The most interesting results are the frequencies of use of the astro-ph server across various subdisciplines of astronomy, and the impact that such posting has on the citation history of the subsequent ApJ papers. By 2002 72% of ApJ papers were posted as astro-ph preprints, but this fraction varies from 22–95% among the subfields studied. A majority of these preprints (61%) were posted after the papers were accepted at ApJ, and 88% were posted or updated after acceptance. Average, ApJ papers posted on astro-ph are cited more than twice as often as those that are not posted on astro-ph. This difference can account for a number of other, secondary citation trends, including some of the differences in citation rates between journals and different subdisciplines. Preprints clearly have supplanted the journals as the primary means for initially becoming aware of papers, at least for a large fraction of the ApJ author community. Publication in a widely-recognized peer-reviewed journal remains as the primary determinant of the impact of a paper, however. For example, conference proceedings papers posted on astro-ph are also cited twice as frequently as those that are not posted, but overall such papers are still cited 20 times less often than the average ApJ paper. These results provide insights into how astronomical research is currently disseminated by authors and ingested by readers.

Keywords: sociology of astronomy — astronomical data bases: miscellaneous

1 Introduction

In 2001 The Astrophysical Journal (ApJ) considered a plan to post preprint versions of its accepted papers on the ApJ web site. As part of this planning we investigated the degree to which ApJ authors already used existing preprint servers, in particular the Los Alamos

arXiv/astro-ph service, when papers were posted in the review cycle, and other patterns of usage. Based on a preliminary study of ~300 ApJ papers published in 2001, we found that the fraction of papers posted on astro-ph was high (73%), but with a wide variation in this fraction across different subfields of astrophysics. We also noted distinct patterns in when papers were posted, with only 64% of such papers posted after the articles were accepted at the ApJ.

As a result of this investigation we decided to make preprints of all accepted ApJ papers available on our website (subject to author permission), in order to make these papers available early to the segment of our reader community that was not making heavy use of the astro-ph service. These results also stimulated us to undertake a larger and more statistically robust study of publication, preprint posting, and citation patterns of ApJ papers. At the heart of the new study is a database containing 1639 papers, equivalent to a full year of papers in the ApJ Part 1 (main journal), and more than five times the number of papers analyzed previously. The database also includes significantly more information about each paper, including preprint information from the astro-ph server, first author demographic data from the American Astronomical Society (AAS) membership directory, and citation data from the NASA Astrophysics Data System (ADS) database.

In this paper we report our findings, with the remainder of this paper organized as follows. In § 2 we describe how the database was constructed, and how we categorized paper subjects and types to analyze demographic trends across our author base. In § 3 we use these data to characterize the trends in publication patterns within the ApJ. In § 4 we analyze statistics on our authors, and in § 5 we look at trends in preprint posting for various subjects and author categories. We present citation statistics on the papers in § 6, and confirm the most interesting result of our study, namely that papers posted prior to publication on astro-ph are cited at approximately twice the rate as those that are not posted prior to publication. We discuss and interpret these results in § 7.
2 Database Construction

All of the ApJ\textsuperscript{1} papers published during the latter halves of 1999 and 2002 form the core of the database. The 2002 data provided a check on any recent changes in demographic trends, particularly with regard to preprint posting, while the 1999 data allowed us to track citation trends for an extended period after those papers were published. There are 795 papers from 1999 and 844 papers from 2002.

For each paper a number of attributes were compiled from four sources. The first source was the electronic ApJ. Attributes recorded included obvious data like titles, page lengths, dates that the papers were received, accepted, and posted, the number of authors, and the names and affiliations of the first authors. No information was gathered about coauthors other than their total number. Authors were designated as working at either U.S. or non-U.S institutions, based on their institutional address published in the paper. When multiple affiliations were given only the first was recorded. Each paper was also placed into one of seven subdisciplines of astronomy. The subdisciplines chosen were cosmology (C), extragalactic astronomy (EG), Milky Way (MW), Galactic ISM (ISM), stellar (S), solar system (SS), and other (O).

The solar system is mainly comprised of papers on solar astrophysics, plus a handful of papers on space physics and other system bodies. The “other” subdiscipline includes papers such as instrumentation, atomic and nuclear process, and analytical and numerical techniques. These subdivisions are somewhat arbitrary, and when a paper covered more than one area we assigned it to its primary category as best as we could. Following the classification scheme outlined in Abt (1993), each paper was also placed into one of the following classifications: theoretical papers containing essentially no observations (T), observational papers presenting new observations (O), papers reanalyzing or re-discussing previous observations (R), and laboratory or instrumentation papers (L). The analysis of these ApJ attributes is given in §3.

The second data source was the AAS membership list provided by the AAS Executive Office, which includes the names and AAS membership status of over 10,000 current and former AAS members. This enabled us to determine the fraction of authors who were AAS members, and also compile age and gender information for those authors.\textsuperscript{2} We were able to determine the gender for all but 6% of the remaining authors, after an exhaustive web search and consultations with colleagues. Results from analysis of these data is presented in §4.

The third data source was the astro-ph preprint server\textsuperscript{3}. Papers with preprints were identified by author and title text searches on the astro-ph search page. When a match was found the astro-ph identification number, the dates of the first and last submission, and the total number of submissions were recorded in our database. The astro-ph submission dates were compared to the submitted and accepted dates of the corresponding ApJ article to determine where the paper was sent first. We then used this information to define four categories of preprints. The “PreApJ” (Pre) group consists of a single preprint arriving at astro-ph near the time of the ApJ submission. Such papers were posted as preprints prior to peer review, and were never updated afterwards. Since 97–98% of published ApJ papers undergo significant revision during the peer review process, this also means that the vast majority of such preprints differ significantly from the accepted and published articles. We defined a second “PostApJ” (Post) group, consisting of single preprint postings that were sent to astro-ph at approximately the same time as the ApJ acceptance date. Apart from minor changes made in copyediting and proofs, the scientific content of these preprints is essentially the same as that of the subsequently published ApJ articles. A third category called “Updated astro-ph” (Up) consists of articles that were posted more than once with astro-ph. Usually these are preprints that were first posted near to the time of submission, and then were updated following peer review and acceptance at the ApJ. The final class, “Unknown astro-ph” (Unk) applied to rare cases where the astro-ph posting dates bore no discernable relation to the journal submission and peer review timelines; fortunately they represent less than 1% of the sample. §5 presents an analysis of the preprint data.

The last data source was ADS\textsuperscript{4}. We were particularly interested in using the ADS citation database to track the papers’ impact, as measured by the number of citations (e.g., Kurtz et al. 2004, Pearce 2004). It is important to emphasize that the ADS citation data are not complete, but by 1999 all of the major journals in astronomy were included, so they should provide reliable information on relative citation trends, with the exception of citation trends across subfields, where the impact of journals outside of mainstream astronomy may be significant. The bibcode for each paper (Schmitz et al. 1995) was used as the input for the ADS query. From the output we recorded the total number of citations, as well as the publication dates of each of the citing papers. Our data include self-citations; it simply was not practical to filter these out among the thousands of citations recorded in our database. However we did determine the overall first author self-citation fraction for our sample (14.8%\textsuperscript{5}), and found that it is relatively constant.

\textsuperscript{1}In order to keep the database as homogeneous as possible we only analyzed papers published in the ApJ Part 1 (main journal); papers published in ApJ Supplement Series and ApJ Letters were not part of this survey. Likewise, editorials and errata were not included.

\textsuperscript{2}These demographic data were only used to track statistical trends in the demographics of our author community; the confidentiality of information on individuals has been preserved.

\textsuperscript{3}http://arxiv.org/archive/astro-ph

\textsuperscript{4}http://adswww.harvard.edu/

\textsuperscript{5}Where our definition of a self citation is when any of the authors of a citing paper is also the lead author of the cited
across the various subdiscipline and demographic categories in our analysis. Therefore we are confident that the inclusion of self-citations does not influence any of the conclusions of our analysis.

Table 1 lists all of the principal attributes used in this analysis, along with their abbreviations as they appear in subsequent tables and figures.

3 Attributes of ApJ Papers

We begin with a brief summary of how the current papers in the ApJ are distributed by type, subject area, authorship, length, and preprint submission fraction. This serves to update previous analyses published by Helmut Abt (references below), and provide a foundation for the other analyses that follow. As might be expected there was little or no significant change in these trends between 1999 and 2002, so in most cases we plot results for both sets of papers combined. The notable exception is in preprint postings, which have increased significantly over the past 5 years, and we present these trends below.

The distribution of papers by subdiscipline and type are given in Figures 1 and 2, respectively. The most popular subdisciplines are extragalactic and stellar with about 28% of the total each. ISM and solar (system) papers each constitute around 15% of the total. Cosmology represents less than 10%, but we have separated it out as a distinct category because these authors are among the heaviest users of the astro-ph server (below). The least numerous are the Milky Way and the “other” subdisciplines, comprising less than 8% of the total combined (the fraction once was higher, but most observational papers on Galactic astronomy now are published in the Astronomical Journal).

When grouped by type, the ApJ is roughly equally divided between theoretical and observational papers (43% and 47%, respectively). The fraction of observational papers has increased by a few percent since 1999, but this may reflect the impact of several large space missions (e.g., Chandra X-ray Observatory), and the recent trend probably is not representative of a long-term change in the Journal. The rediscussion and laboratory papers have remained constant at about 8% and 2%, respectively.

These data can be compared to the analysis of Abt (1993) to see how the breakdown has changed over the past 40 years. Abt’s published data set included all the papers published in the first six months of 1962, 1972, 1982, and 1992 for the ApJ (including Letters and Supplements), the Astronomical Journal, and the Publications of the Astronomical Society of the Pacific. Dr. Abt kindly supplied us with his original data, so we could recompile the type percentages for the ApJ main journal alone. To minimize fluctuations due to small number statistics we also include papers published in the latter half of 1962 to double the original 96 papers. Figure 2 shows the results. Interestingly, the nearly equal division between theoretical and observational papers has persisted at the ApJ for at least 40 years. The other two classifications are also relatively constant.

Table 2 presents a variety of other demographic data for our combined 1999/2002 sample, including total number of authors, paper length and acceptance time, summarized for the ApJ as a whole. Means, 1σ standard deviations in the means, and median numbers are given in each case. In most instances there is a remarkable uniformity in author habits across the range of disciplines represented by the ApJ. However there are notable exceptions that we highlight below and in § 4.

The average number of authors in 1999–2002 was 4.2, and increased from 4.0 ± 0.1 to 4.5 ± 0.2 over that 3-year period. This continues a long-term increase documented previously by Abt (2000). Interestingly, the median number has been growing more slowly with time (currently standing at 3), suggesting that much of the average increase is due to a growing subpopulation of papers with very large numbers of authors. There is also a pronounced distinction between theoretical and observational papers, which differ by roughly a factor of two in numbers of authors, whether measured by means or medians. This is not very surprising given the advent of large multi-user observational facilities and large surveys, but it does underscore the presence of an increasing gulf in the prevailing manners and cultures in which theoretical and observational research are conducted in astronomy.

The lengths of ApJ papers also show a slow but relentless growth, reaching 11.5 pages in 1999/2002 and nearly 12 pages today. Again this follows a long-term evolutionary trend (Abt 1981). There is no significant difference across subfields or paper type, apart from papers in the “Other” category, mainly laboratory or analytical spectroscopy papers, that tend to be somewhat shorter on average. Likewise there is little significant difference in peer review times (the time between initial submission and final acceptance of a paper) across subdisciplines. The 35% decline in the 2002 data is due to the introduction of web-based peer review and tighter editorial controls on the peer review process.

4 Demographic Trends Among First Authors

The first author’s age during the year of publication is provided in Table 3. The average ages are almost 40 while the median is 37. There is an interesting anti-correlation between median age and subject area when measured in terms of distance from the Earth, doubtless a reflection of the evolution in research interests of young scientists. In addition, the median first-author age for an observational paper is 2-3 years younger than authors of theoretical papers.

Other demographic trends are summarized in Figure 3. In 1999–2002 37% of ApJ first authors worked at an institution outside of the U.S.; the ApJ truly is an international journal. Interestingly, a minority of

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paper. This method only provides a lower limit but is consistent with other studies (e.g. Trimble 1986)
first authors—only 45%—were active AAS members in 2002, somewhat surprising given the fact that the ApJ is owned and administered by the AAS. Among all ApJ authors based in the U.S., only 63% were active members 2002.

Our data reveal some interesting patterns in publication according to first author gender (see Figure 3 and Table 3). Among the 94% of all papers where the author’s gender could be established, 15.4% of first authors were women. This can be compared to the findings of the recent survey of women in astronomical institutions by Hoffman & Kwitter (2003) 6. The fractional representation of women in that survey among postdocs, assistant, associate, and full professors is 20%, 17%, 15%, and 8%, respectively (with an average of 12% for all professors). The 15.4% representation among ApJ first authors falls in the middle of these numbers, and is roughly consistent with the average age of 37–40 for the author population.

Closer examination of Table 3 reveals strong patterns in these percentages across subdisciplines and paper types. Less than 9% of papers in cosmology are authored by women, compared to 18.5% of observational papers, though the distinctions are decreased in the ISM. Likewise less than 12% of theoretical papers overall are authored by women, compared to 18.5% of observational and reanalysis papers. These are not second-order reflections of age demographics, as Table 3 will testify. They reflect systematic differences in participation of women among subdisciplines, whether by choice or by retention.

5 Preprint Demographics and Trends

Table 4 summarizes the preprint posting habits of ApJ authors. In this case we have tabulated results for 1999 and 2002 separately, to illustrate the increase in postings over time. By 2002 72% of all ApJ papers were posted as preprints at some time prior to publication. This fraction increased from 61% in 1999, though a more detailed look at the temporal trends suggests that this fraction has leveled off at 72–75% since 2001. It is notable that a similar fraction of authors (~80%) elect to post their accepted ApJ manuscripts on our own website. The population of “non-posters” includes scientists working in fields where astro-ph is not widely used (below), and a smaller fraction of authors who choose not to utilize the preprint posting services at all.

One of the pleasant surprises of this study (to us) was the way in which authors use the preprint posting services. A majority of ApJ authors (61%) did not post their preprints until the paper had passed peer review and been accepted for publication. The remaining authors posted their paper for the first time at submission, and the fraction of authors who post early increased significantly between 1999–2002. However an increasing portion of those authors went to the trouble of updating their astro-ph postings after acceptance; in fact only 11% of authors posted only their submitted version of an accepted ApJ paper. Of course this says nothing about the astro-ph postings for papers that are rejected or otherwise remain unpublished, and the updates only are useful for the few astro-ph users who download and read the updated postings. But it is reassuring to know that there is ~90% correspondence between the preprints and the accepted manuscripts after the time of acceptance.

Table 5 and Figure 4 show the same information but now broken down by subdisciplines and paper types. Some trends are common to most fields, most notably the general increase in overall postings between 1999 and 2002. More striking are the differences in preprint posting practices among different subfields. The posting rates are the highest in cosmology (95% of all published ApJ papers) and extragalactic astronomy (90%); in these fields nearly every significant ApJ paper first appears on the astro-ph server. At the other extreme is solar system (including solar astrophysics), where only 22% of papers are posted. This reflects a curious general trend between astronomical distance and preprint posting frequency. However even in the solar system category the usage of the server is increasing over time.

Our data reveal other interesting demographic trends in the preprint posting habits of our authors. In most fields theoretical papers are posted more frequently than observational papers, though the distinctions are decreasing over time. Authors who use astro-ph are significantly younger than authors who do not post on the server (median age 35 years vs 44 years, respectively). U.S. authors use astro-ph slightly more often than non-U.S. authors (62.5% vs 58%). Usage by male and female authors is the same within the statistical errors.

Many of the differences in overall use of astro-ph across subdisciplines are also mirrored in the posting patterns. For example in 2002 only 23% of cosmology preprints were posted for the first time after peer review, compared to 61% for all ApJ papers. Cosmologists not only are the heaviest users of the system, they also are the quickest to post new results. Cosmology stands out uniquely in this regard; in every other subdiscipline we considered a majority of papers (57–80%) of papers were posted for the first time after acceptance (exceptions exist in some small subfields, including gamma-ray burst observations and gravitational microlensing, where rapid release of data is especially important). There also is a sharp contrast between theoretical papers, which are posted early much more frequently than the other types of papers (53% vs 0–33% for observational, rediscussion, and laboratory papers).

Many of these trends are understandable in terms of the different prevailing practices and subcultures within astronomy. Theoretical papers often are posted early so the authors can obtain independent feedback from colleagues during the peer review process, and in some cases with the intent of establishing scientific priority for new ideas. Observers tend to be more conservative, partly out of a desire to confirm the veracity of their

6The poster and the raw data is available at http://www.ruf.rice.edu/~jhoffman/stats/.
data before disseminating it widely, and in some cases to protect their proprietary interest in the data until the respective paper is accepted for publications.

6 Citation Patterns

In order to analyze the trends in citation rates for our papers we compiled citation data from the ADS database in the summer of 2003. In order to have a reliable time base over which to collect these data we restricted all of the citation analysis to the ApJ papers in the 1999 subset. Table 6 summarizes the mean and median number of ADS citations, averaged according to subdiscipline, paper type, and demographic category. These values are integrated over the entire citation lifetime of the paper up to mid-2003 (for reference, the average citation frequency for ApJ papers, during the first two years after the publication year, is 6.6 citations/paper/year.

6.1 Citation Rates Across Subfields and Paper Characteristics

We were somewhat pleasantly surprised to find that citation rates of ApJ papers do not differ very widely across subdisciplines or demographic categories. Some patterns are evident; citation rates are highest among the mainstream categories of astronomy (cosmology, extragalactic, Galactic, stellar), where large numbers of papers are written, and systematically lower in the solar system and “other” categories, where the number of practicing scientists is much lower, and where the ADS citation data are likely to be more incomplete. An anomaly we do not understand is the significantly lower citation rate for papers in the Galactic/ISM subfield. There is also a small but significant difference in the citation frequencies for ApJ papers by U.S. and non-U.S. authors. Part of this is a second-order effect of the differences in citation rates by subfield alluded to above.

Abt (1984) showed that the mean number of citations increased linearly with both paper page length and the number of authors. Figures 5 and 6 show that these trends are still valid. The points show the mean citation rates (and standard deviations) as functions of paper length (Fig. 5) and number of authors (Fig. 6), while the histograms show the number distributions of papers by length and author number, with the respective scales given on the righthand axis of each plot. The number of single-author papers has steadily declined throughout the years, declining from 40% of all papers published in 1974 (Abt 1984) to 13% in 1999. Over the same period the fraction of papers with more than 6 authors increased from 3% to 18%. The single-authored paper is becoming an endangered species!

6.2 Demographic Trends

Figure 7 shows the mean and the one sigma standard deviation of the mean ADS citations as a function of first author age (left ordinate) and the age distribution (right ordinate). If taken literally the results suggest that the impact of an average astronomer’s papers peaks during their 30’s, but this peak is not statistically significant. What is significant is a very steep decline in citation frequency after age 50. This may partly reflect external factors such as subfield of interest and preprint posting practices (§ 6.3), but age itself clearly is important.

The data also show some differences in citation frequencies between papers by male and female first authors, but the patterns are inconsistent; while the average citation rates for male first authors are higher, the median rates for male first authors are lower. Further investigation we found that the difference in mean rates is driven by a small number of very highly cited papers that skew the averages. This is shown in Figure 8, which compares the normalized citation distributions for papers with male and female first authors. The distributions for men and women are virtually the same (within statistical errors) until one reaches papers with 50 or more citations. Among the latter super-cited papers all but two have male first authors.

With the limited sample size we cannot discern for certain whether this difference in very highly cited papers is a product of small number statistics or a genuine imbalance in the authorship of major, highly-cited papers. However we would not be surprised if part of the difference is real, because it would fall in line with other known demographic trends, such as the strong under-representation of women among the ranks of full professors and equivalent rank staff positions in astronomy (Hoffman & Kwitter 2003), and the strong (and disturbing) under-representation of women among the major AAS prize winners over the past two decades. Without a firmer statistical foundation we would caution against overinterpreting these citation patterns, but we intend to collect more data on these rates over time to ascertain whether the gender-based differences in citation patterns persist.

Table 6 also compiles the citation frequencies as functions of the first author’s AAS membership status and country. Papers by active AAS members and U.S.-based authors are cited ~30% more frequently than papers by non-AAS members and non-U.S. authors. In this case much of the difference can be attributed to other factors, such as differences in subdiscipline distributions and the lesser likelihood that non-U.S. authors post their papers on astro-ph (§ 6.3).

6.3 Effect of Preprint Posting on Citation Rates

Table 6 also tabulates the citations separately for papers that were posted on astro-ph and those that were not. These reveal the most interesting result of our entire study, namely that ApJ papers posted prior to publication as astro-ph preprints are cited more than twice as often as papers that are not posted on astro-ph. This pattern persists across every subdiscipline and subcategory of paper we analyzed.

How does one interpret this striking difference in ci-
tation frequencies? At first we speculated that it resulted from the longer visibility of a paper that was posted as a preprint. For papers published in 1999 there was a lag of nearly a year between average submission and publication time (since reduced by 40%), so papers that were posted as preprints have a longer effective citation lifetime. To test this hypothesis we tabulated the time histories of the citations for 1999 papers, and plotted them separately according to whether they were also posted on astro-ph. The results are shown in Figure 9. As expected, the papers that had been circulated as preprints enjoyed a surge in early citations that was not mirrored in the papers that were seen for the first time in the Journal. However the same plot shows that the difference in citation rates persists for more than 3 years after the ApJ paper is published. This cannot be an artifact of a longer “shelf life” of the preprints; instead it strongly suggests that at least half of the author community only becomes aware of other papers when they are posted on astro-ph. We discuss the implications of these findings further in § 7.

We used the same data to determine whether citation rates were influenced by when an author posts their paper to the preprint server. Figure 9 also subdivides the astro-ph posted papers by those posted at submission (“Pre” and “Up”, solid line), and those posted after peer review and acceptance (“Post”, dotted line). The papers with the earliest preprint postings show a marginally higher citation rate, which may simply reflect their slightly longer visibility time. Over long periods the two citation distributions are indistinguishable. We should note that in making this comparison we excluded 5 preprints in the extreme tail of the citation distribution (>100 citations). Most of these were “Pre” postings of time-critical data (e.g., gamma-ray burst observations). This 2% of the sample is sufficient to boost the citation rate of the entire “Pre” sample by nearly 20%. However the difference appears to reflect the nature of these particular papers, and not the effects of preprint posting habits. We intend to update our data in the future to confirm whether the posting time has negligible effect on the impact of the subsequently published paper.

Table 6 also lists the distribution of citations for the various subcategories of papers. In all subdisciplines and classes the number of citations is significantly higher for papers submitted to astro-ph compared to their ApJ-only counterparts. However the magnitude of the difference varies widely between subdisciplines, in ways that mirror the overall preprint posting pattern in those subfields. For example in cosmology, where 85% of ApJ authors post on astro-ph, the citation rates between posted and unposted papers differ by more than a factor of ten! It appears that papers in this field that are not posted on astro-ph are virtually ignored. In contrast, in the ISM field posting of preprints has only a small (~30%) effect on citation rates, as compared to the factor-of-two average for all ApJ papers. This partly reflects the lower overall penetration of astro-ph into this subfield, and the availability of other electronic newsletters and alerting services for new papers parts of this field.

7 Comparison with Non-Peer-Reviewed Papers

We have shown that the increased visibility of papers afforded by preprint postings has a significant (factor-of-two) effect on the subsequent citations to those papers. How does this compare to the other factors that influence the impact of an article? Citation statistics for the major journals are compiled by the ISI, and they show a dispersion of approximately a factor of two among citation rates for the half-dozen major astronomy and astrophysics journals, and roughly an order of magnitude range over all of the significant journals. So the change in impact from posting a paper on astro-ph is comparable to the differences in overall impact among the major journals.

Less information is available on how publishing in a peer-reviewed journal overall influences a paper’s impact, and how posting on astro-ph increases the visibility of non-peer-reviewed articles. To provide at least a rudimentary answer we used ADS to compile citation frequencies for 2673 papers that appeared in 31 conference proceedings published in 1999. We took pains to select a distribution of subdisciplines that mirrored the ApJ paper distribution for the same year, and ranged in visibility from major symposia to smaller meetings. Between 1999 and mid-2003, the same time base for the ApJ paper data shown in Table 6, these papers were cited a total of 2181 times, for a mean of 0.82 citations/paper. This compares to a mean of 16.4 citations/paper for the 1999 ApJ papers, exactly 20 times higher. We find a similar ratio when we compare the official ISI impact factors for the ApJ with those for IAU symposia volumes, so we believe that our methodology is robust. Similarly, Kurtz et al. (2004) found that 68% of 1995 ApJ papers were cited in the year 2000 while only 1.6% of Bulletin of the American Astronomical Society abstracts published 1995 were cited in the 2000.

In order to assess the impact of preprint posting on these articles, we selected a subset of the more highly cited proceedings, determined which papers had been posted as preprints on astro-ph, and compared citation rates as described earlier for ApJ papers. We found that posting a conference paper on astro-ph increased the impact of the subsequent paper by a factor of 2.2 on average, nearly the same as the factor of 2.05 enhancement for ApJ papers. So preprint posting increases the relative visibility of non-peer-reviewed papers by a comparable factor, but the factor-of-20 difference between proceedings papers and ApJ papers remains the same regardless of whether the respective papers are posted on astro-ph or not. This should serve as a caution to anyone who might believe that preprint posting alone is sufficient to assure that a paper is widely recognized and cited.

8 Discussion: Implications for Electronic Publishing

What lessons can we draw from these results? One implication is unmistakable—authors who wish to maxi-
mize the visibility of their papers should post their articles to the large e-print servers such as astro-ph. Exactly when the paper is posted appears to have little effect on citation rates. Another lesson to be gleaned from these results is that as the pace of astronomical discovery has accelerated over the past decade, astronomers want to learn about new results as quickly as possible, rather than wait the additional weeks or months for final, edited versions of the results to appear.

Although the use of astro-ph as an alerting service is rapidly achieving near-universal use in the astrophysics community, authors remain highly divided about the contents and timing of their postings. At this time the ApJ author community (that is, the community of authors who write papers that are eventually accepted) is roughly equally divided between those who use astro-ph as a posting service for accepted, peer-reviewed papers, and those who post papers before they are reviewed, either to establish priority or to solicit feedback from colleagues during the peer review cycle. These cultural differences are strongly polarized across subfields and between observers and theorists. To some extent these patterns pre-date the era of electronic preprints, but the relative convenience and low cost, worldwide dissemination of results that is offered by the e-print servers clearly has caused more authors to migrate toward the bulletin board model. It will be interesting to see whether this trend continues in the future.

Our data document how thoroughly the astro-ph preprint server, over the time span of a decade, has supplanted the departmental preprint shelves and the personal mailings of preprints as the primary means that astronomers become aware of new papers in their field. One striking feature in Table 6 is the relative consistency of citation rates across subfields and types, when preprints of the papers are posted on astro-ph; the citation frequencies rarely vary by more than ±20–30% of the average rate. In contrast, the citation rates for papers that are never posted as preprints, apart from being a factor of two lower overall, fluctuate from field to field by more than a factor of five. As a larger fraction of papers is posted as preprints, the visibility of those remaining papers that are not posted on e-print servers is sure to decline even further, as it has already in cosmology. Just as publishing in refereed journals is regarded as an essential prerequisite for establishing the credibility and documenting an individual’s or group’s scientific research, posting this work on the arXive server is becoming essential for disseminating that research to the largest possible audience.

We should caution the reader that other factors probably contribute to the difference in citation frequency between preprint-posted and unposted papers. For example, authors with new results they believe to be of special significance are much more likely to post their results on astro-ph. The same is true for papers with particular time-critical value. These effects will always cause pre-posted papers to be more highly cited on average, and without an independent means to rank paper quality it is impossible to disentangle them from the effects of increased visibility afforded by astro-ph.

Given that e-print posting clearly is becoming a central factor influencing the visibility and citation of subsequently published journal articles, does this mean that the journals themselves are becoming irrelevant in the process of scientific communication? We think not. Although the preprint servers are filling a vital function by disseminating these articles quickly and efficiently, all of the other attributes of the papers that make them so valuable and citable are enforced by the peer review and the other editorial requirements of the respective journals. All of the citation data presented here refer to accepted and published ApJ papers, which were vetted by peer review and stringent standards of copyediting, bibliographic referencing, and data presentation. The corresponding preprints, regardless of when they were posted, were all prepared with the expectation of meeting these rigorous ApJ publication standards. In the absence of such editorial standards and controls it is naive to expect that papers would continue to maintain this level of scientific quality, English presentation, and clarity of tables, figures, and referencing entirely on their own. If one wants to visualize what a fully open-access, self-reviewed literature in astronomy might look like, the conference proceedings discussed earlier provide an interesting analogy. Conference papers offer many of the features of a free-publication system, with little or no peer review, minimal production standards, no copyediting, and when posted on astro-ph virtually free distribution and access, with equal visibility to journal articles. Nevertheless such papers are cited only 5% as often as comparable ApJ papers, even when posted on astro-ph. To be fair the two sets of papers are usually intended for entirely different purposes, but the comparison underscores the critical role that the destination publishing source plays in dictating the quality and long-term value of their respective preprints.

We believe instead that our study illustrates the strength of the symbiosis that currently exists between the major peer-reviewed journals, the arXive preprint server, and the NASA ADS system. The journals largely set the scientific and editorial standards that are replicated in much of the preprint literature, while the e-print servers have increasingly supplanted much of the role of the journals as the first access point to new research results, with a publication model that embodies superb distribution efficiency and ease of use. Even if each journal were able to replicate this efficiency the advantages of a single consolidated source for preprints, covering all journals and other publications, clearly make it the model of choice for preprint distribution. Although any system of publishing can be improved, the vitality of astronomical publishing can be attributed to the effective combination of a family of peer-reviewed electronic journals with and an efficient and user-friendly preprint distribution system, and a powerful bibliographic database system at ADS linking all of these resources.
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| Attribute     | Acronym | Definition/Example                                                                 |
|---------------|---------|-----------------------------------------------------------------------------------|
| Cosmology     | C       | Galaxy formation, Cosmic Microwave Background, Hubble and cosmological constants   |
| Extra-Galactic| EG      | High-redshift galaxies, Active Galactic Nuclei, InterGalactic Medium, galaxy clusters |
| Milky Way     | MW      | Milky Way structure, Galactic center, globular clusters                            |
| Galactic ISM  | ISM     | Galactic Super Nova remnants, InterStellar Medium, and star formation              |
| Stellar       | S       | All stars including Supernova and Gamma-Ray bursts                                 |
| Solar system  | SS      | Sun and solar system objects                                                       |
| Other         | O       | Instrumentation, atomic and nuclear processes                                      |
| Theoretical   | T       | Theory paper with no observations                                                 |
| Observational | O       | New observation paper                                                              |
| Rediscussion  | R       | Paper discussing previous observations                                            |
| Laboratory    | L       | Laboratory or instrumentation                                                     |
| PreApJ        | Pre     | One preprint posted before ApJ submission.                                         |
| PostApJ       | Post    | One preprint posted after ApJ acceptance.                                          |
| Updated       | Up      | Multiple preprint submissions.                                                     |
| Unknown       | Unk     | The preprint’s posted date does not match either the ApJ submitted or accepted dates. |
| Type                  | 1999          | 2002          |
|----------------------|---------------|---------------|
|                      | Mean Median   | Mean Median   |
|                      | Number of Authors | 4.0±0.1  3  | 4.5±0.2  3  |
|                      | Published page length | 11.4±0.2  10 | 11.6±0.2  10 |
|                      | Acceptance time in days | 177±5  142 | 133±4  95 |

For the combined 1999 and 2002 data sets.

| Type                  | Sample size | Mean Age ± Median | Median Age | Total Papers | M/F Ratio | Unk (%) |
|----------------------|-------------|-------------------|------------|--------------|-----------|---------|
|                      |             | Age               |            |              |           |         |
| C                    | 50          | 36.0±1.3         | 35         | 144          | 10.4      | 5       |
| EG                   | 235         | 38.2±0.6         | 36         | 452          | 4.2       | 5       |
| MW                   | 39          | 33.7±1.2         | 31         | 71           | 3.8       | 6       |
| ISM                  | 139         | 40.0±1.0         | 36         | 249          | 5.1       | 5       |
| S                    | 256         | 40.4±0.7         | 38         | 461          | 6.2       | 7       |
| SS                   | 88          | 44.2±1.3         | 42         | 213          | 7.4       | 9       |
| O                    | 14          | 43.5±2.5         | 46         | 49           | 13.0      | 14      |
| T                    | 292         | 39.1±0.6         | 35         | 711          | 7.4       | 8       |
| O                    | 461         | 40.1±0.5         | 38         | 775          | 4.4       | 4       |
| R                    | 64          | 37.9±1.3         | 36         | 125          | 4.9       | 6       |
| L                    | 4           | 42.8±3.2         | 46         | 28           | ∞         | 27      |
| All                  | 821         | 39.6±0.4         | 37         | 1639         | 5.5       | 6       |

Note. — See Table 1 for explanations of subdiscipline and type codes.

For the combined 1999 and 2002 data sets.

Fraction of total sample that couldn’t be assigned a gender.

Number of papers where the first author’s age is known.

| Time (mm/yy) | Total astro-ph (%) | Pre (%) | Post (%) | Unk (%) | Up (%) |
|--------------|--------------------|---------|----------|---------|-------|
| 07-12/99     | 795                | 61      | 14       | 68      | <1    | 18    |
| 02-03/01b    | 296                | 73      | 19       | 64      | 2     | 16    |
| 07-12/02     | 844                | 72      | 11       | 61      | <1    | 27    |

See Table 1 for an explanation of astro-ph codes.

From original unpublished AAS Journal - astro-ph survey.
| Grouping   | Total Papers | Pre (%) | Post (%) | Unk (%) | Up (%) |
|-----------|--------------|---------|----------|---------|--------|
| **Subdiscipline (1999)** | | | | | |
| C         | 56           | 21      | 43       | 2       | 34     |
| EG        | 181          | 7       | 82       | 0       | 10     |
| MW        | 30           | 20      | 57       | 0       | 23     |
| ISM       | 51           | 8       | 76       | 2       | 14     |
| S         | 135          | 19      | 61       | 1       | 19     |
| SS        | 15           | 20      | 53       | 0       | 26     |
| O         | 16           | 38      | 44       | 0       | 19     |
| **Subdiscipline (2002)** | | | | | |
| C         | 75           | 25      | 23       | 0       | 52     |
| EG        | 201          | 6       | 69       | 0       | 25     |
| MW        | 26           | 15      | 61       | 0       | 23     |
| ISM       | 79           | 6       | 80       | 0       | 14     |
| S         | 194          | 11      | 59       | 1       | 29     |
| SS        | 26           | 12      | 77       | 4       | 8      |
| O         | 7            | 14      | 57       | 0       | 29     |
| **Classification (1999)** | | | | | |
| T         | 214          | 22      | 50       | 1       | 26     |
| O         | 219          | 8       | 81       | <1      | 11     |
| R         | 46           | 9       | 80       | 0       | 11     |
| L         | 5            | 0       | 100      | 0       | 0      |
| **Classification (2002)** | | | | | |
| T         | 264          | 17      | 47       | <1      | 36     |
| O         | 295          | 6       | 75       | <1      | 19     |
| R         | 47           | 9       | 57       | 0       | 34     |
| L         | 2            | 0       | 100      | 0       | 0      |
Table 6: Distribution of ADS citations

| Grouping | All papers | astro-ph papers | Non astro-ph papers |
|----------|------------|-----------------|---------------------|
|          | # Papers   | Mean ± Median   | # Papers            | Mean ± Median   | # Papers   | Mean ± Median   |
| All      | 795        | 16.4 ± 0.8      | 484                 | 20.5 ± 1.2      | 311        | 10.0 ± 0.8      |
|          |            | 10              | 13                  | 6               |
| Subdiscipline |          |                 |                     |                 |                     |
| C        | 65         | 19.7 ± 3.4      | 56                  | 22.5 ± 3.8      | 9          | 2.2 ± 0.6       |
| EG       | 226        | 19.6 ± 2.0      | 181                 | 21.8 ± 2.4      | 45         | 10.4 ± 1.4      |
| MW       | 34         | 18.5 ± 2.9      | 30                  | 20.1 ± 3.1      | 4          | 6.3 ± 1.7       |
| ISM      | 130        | 12.7 ± 1.3      | 51                  | 14.8 ± 1.6      | 79         | 11.4 ± 1.8      |
| S        | 213        | 17.5 ± 1.6      | 135                 | 21.0 ± 2.2      | 78         | 11.3 ± 2.1      |
| SS       | 94         | 9.9 ± 1.3       | 15                  | 16.1 ± 3.4      | 79         | 8.8 ± 1.4       |
| O        | 33         | 11.0 ± 2.4      | 16                  | 16.3 ± 4.1      | 17         | 6.0 ± 1.8       |
|          |            |                 |                     |                 |                     |
| Classification |          |                 |                     |                 |                     |
| T        | 360        | 15.1 ± 1.1      | 214                 | 19.4 ± 1.7      | 146        | 8.8 ± 0.9       |
| O        | 351        | 16.8 ± 1.4      | 219                 | 20.1 ± 2.0      | 132        | 11.2 ± 1.5      |
| R        | 67         | 23.2 ± 3.3      | 46                  | 28.0 ± 4.1      | 21         | 12.6 ± 4.5      |
| L        | 17         | 7.4 ± 1.9       | 5                   | 12.4 ± 4.9      | 12         | 5.3 ± 1.6       |
| Gender   |            |                 |                     |                 |                     |
| Male     | 638        | 17.2 ± 1.0      | 397                 | 21.3 ± 1.5      | 241        | 10.5 ± 1.0      |
| Female   | 112        | 14.1 ± 1.2      | 66                  | 17.2 ± 1.7      | 46         | 9.8 ± 1.3       |
| AAS      |            |                 |                     |                 |                     |
| Member   | 352        | 19.5 ± 1.6      | 223                 | 23.9 ± 2.3      | 130        | 12.1 ± 1.7      |
| Nonmember| 443        | 13.8 ± 0.8      | 261                 | 17.6 ± 1.1      | 181        | 8.4 ± 0.8       |
| Country  |            |                 |                     |                 |                     |
| USA      | 501        | 17.7 ± 1.2      | 313                 | 21.9 ± 1.8      | 188        | 10.6 ± 1.1      |
| Other    | 294        | 14.1 ± 0.9      | 170                 | 17.8 ± 1.3      | 124        | 8.9 ± 1.2       |
| All      | 795        | 16.4 ± 0.8      | 484                 | 20.5 ± 1.2      | 311        | 10.0 ± 0.8      |

Note. — The mean and median values for the astro-ph types “Pre” + “Up” and “Post” are 24.8 ± 3.2 and 15 and 18.1 ± 1.0 and 12 respectively.
Fig. 1.— Distribution in the ApJ by subdiscipline for the combined 1999 and 2002 data sets. See Table 1 for an explanation of the subdiscipline codes.

Fig. 2.— Classification distribution as a function of time. The first four points are from Abt (1993) excluding all but ApJ papers (see text). The last two points are from this study. The solid, dotted, dashed, and dot-dashed lines are the observational, theoretical, rediscussing, and laboratory papers, respectively.

Fig. 3.— ApJ distribution percentages by the first author’s country, AAS membership, and gender for the combined 1999 and 2002 data sets.

Fig. 4.— Astro-ph submission percentages as a function of subdiscipline (left figure) and classification (right figure). The left and right bars of each column give the percentages in 1999 and 2002, respectively.

Fig. 5.— ADS citations as a function of published page length in 1999. The boxes (left ordinate) give the mean and 1σ uncertainty range for each bin. The histogram of the distribution (right ordinate) is provide beneath the citation data.

Fig. 6.— ADS citations as a function of number of authors (left ordinate) and the citation distribution (right ordinate). The boxes give the mean and 1σ uncertainty range for each author bin.
Fig. 7.— ADS citations as a function of first author age in 1999. The boxes (left ordinate) give the mean and 1σ uncertainty range for each bin. The histogram of the distribution (right ordinate) is provide beneath the citation data.

Fig. 8.— Histogram of ADS citations as a function of gender. The solid line is for males and the dotted line is for females. Both lines have been normalized by the total number of cites per gender.

Fig. 9.— Histogram of ADS citations as a function of astro-ph submission type. The solid line are papers submitted to astro-ph at the same time as ApJ (“Pre” and “Up”), the dotted line are papers submitted to astro-ph after ApJ acceptance (“Post”), and the dashed line are papers never submitted to astro-ph. Five papers with anomalously high citations have been excluded from the statistics (see text).