Hubble Space Telescope Science Metrics

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ABSTRACT. Since its launch in 1990 April, the Hubble Space Telescope (HST) has produced an increasing flow of scientific results. The large number of refereed publications based on HST data permits a detailed evaluation of the effectiveness of this observatory and its scientific programs. This paper presents the results of selected science metrics related to paper counts, citation counts, citation history, high-impact papers, and the most productive programs and most cited papers through the end of 2003. All these indicators point toward the high-quality scientific impact of HST.

1. INTRODUCTION
The Hubble Space Telescope (HST), orbiting the Earth at an altitude of about 600 km, is the product of an international collaboration between the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). Its position high above any atmospheric turbulences, and the high quality of its instruments, provide the astronomical community with observations of excellent resolution and sensitivity in the wavelength domains of the ultraviolet, visible, and near-infrared.

HST has produced an increasing flow of scientific data since its launch by the space shuttle Discovery in 1990 April. After more than a decade of Hubble observations, the large number of publications based on HST data provides a statistically sound basis to determine the scientific effectiveness of this observatory.

There are numerous previous studies about science metrics in astronomy: Abt (1981) studied the citation histories for papers published in 1961. Trimble (1995) analyzed papers and citation counts for papers based on data collected at large telescopes. Benn & Sánchez (2001) estimated the participation of different facilities in the most cited papers in astronomy from 1991 to 1998. Crabtree & Bryson (2001) examined in detail the productivity and impact of the Canada-France-Hawaii Telescope (CFHT).

Improvements in databases for paper and citation counts have prompted the Space Telescope Science Institute (STScI) to develop a new standard methodology to define the scientific impact of HST through quantitative and objective metrics. The aim is twofold: (1) to monitor the use of the telescope in order to improve and maximize its scientific output through adjustments in the process of the allocation of observing time, and (2) to report to funding agencies, various governing committees, and to the astronomical community. See Meylan et al. (2003) for a succinct presentation of some of our metrics results.

There are two straightforward and relevant measures of the effectiveness of a telescope: the number of refereed papers based on data obtained by the telescope, and the citation count for those papers. It is obvious that the full scientific impact of a facility may also be evaluated through other metrics, such as the number of press releases, the “most important” discoveries, etc. The aim of this paper is to show the results of the first two metrics (paper and citation counts), both objective quantities that can be reproduced and verified by other authors.

The content of this paper is as follows: § 2 describes the way we search and identify refereed papers using HST data, § 3 presents the statistics on the numbers of papers and their citations, and § 4 defines and discusses the so-called “high-impact papers.” Sections 5 and 6 present some highlights of the science produced by HST through the top 10 most productive programs and top 10 most cited HST papers. This paper is devoted to HST publications only; comparisons with other telescopes will be done in the near future through collaborations with those facilities.

2. IDENTIFICATION PROCESS OF REFEREED PAPERS USING HST DATA

There have been various definitions of what constitutes “a paper based on HST data.” Some of these definitions require that of the total amount of observational data used in a paper, at least 50% of them originate from HST. Others do not include papers based on archival data. Since it is impossible to define precisely and consistently the fraction of HST data used in a given paper, we adopt the simplest possible definition: “a paper based on HST data” is a paper benefiting directly from HST observation. Such a paper must contain at least an HST image, an HST spectrum, or new numbers derived directly from HST data. All papers based on data retrieved from the HST archives

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are included. We take into account papers using archival data either for reanalysis or for new scientific aims. This broad definition has also been adopted by other observatories (e.g., ESO), but it has to be clearly stated if the numbers are to be used for comparisons among different facilities, which is not our aim in this paper.

Most of the information we use comes directly from ADS, the NASA Astrophysics Data System hosted in Cambridge, MA, at the Harvard-Smithsonian Center for Astrophysics (see Kurtz et al. 2000).

We run a boolean logic query on ADS with the following search string: “HST OR (HUBBLE AND SPACE AND TELESCOPE) OR WFPC OR WFPC1 OR WFPC2 OR (WF AND PC AND HST) OR (WIDE AND FIELD AND PLANETARY AND CAMERA) OR FGS OR (FINE AND GUIDANCE AND SENSORS) OR HSP OR (HIGH AND SPEED AND PHOTOMETER) OR FOC OR (FAINT AND OBJECT AND CAMERA) OR FOS OR (FAINT AND OBJECT AND SPECTROGRAPH) OR HRS OR GHRS OR (GODDARD AND HIGH AND RESOLUTION AND SPECTROGRAPH) OR STIS OR (SPACE AND TELESCOPE AND IMAGING AND SPECTROGRAPH) OR NICMOS OR (NEAR AND INFRARED AND CAMERA AND MULTI AND OBJECT AND SPECTROMETER) OR ACS OR (ADVANCED AND CAMERA AND SURVEYS).”

The above query produces a list of papers, with some wrong hits (HST also stands for Hawaiian Standard Time!). Each paper is then downloaded and read in order to confirm whether it is a genuine HST paper. Since ADS allows queries of only the abstract of a paper and not its full text, hard copies of all refereed journals are searched manually by the staff of the STScI Library.

For each identified HST paper, we search for the program(s) ID(s) of the HST data used. A link is then established in the Multimission Archive at Space Telescope (MAST) between the paper and the program(s). There is at least one program ID for each HST paper. For each HST program, the list of publications that it has generated is accessible online to the astronomical community through the MAST Web site by entering the proposal program ID.

Our list of papers that are recognized as using HST data is publicly available online and can be accessed by the astronomical community through ADS by activating the HST filter at the “Select References In:” option. MAST automatically sends a monthly electronic update of the list of publications to ADS.

It is worth mentioning that the amount of work required to identify a paper and link it to a program is sometimes very onerous. We have encountered many stumbling blocks, often created when authors provide the wrong program IDs. We have even identified a few papers that wrongly claimed to be based on HST data.

In order to test the completeness of our list of refereed papers, we contacted all of the principal investigators (PIs) of programs in Cycles 4 and 5 for which we could not find any refereed publications arising from their data, and the PIs confirmed that there were no additional papers. We expect that a few papers may have been missed by our search, but the number must be very small, certainly less than a few percent.

3. Paper and Citation Counts Metrics

Most of the HST refereed papers (about 90%) are published in the five major refereed journals: the Astrophysical Journal (ApJ), the Astronomical Journal (AJ), Astronomy and Astrophysics (A&A), the Monthly Notices of the Royal Astronomical Society (MNRAS), and the Publications of the Astronomical Society of the Pacific (PASP). Of course we also count all papers in the other refereed journals, such as Nature and Science. In this paper, we take into account only refereed publications published by the end of 2003 December.

3.1. Paper Counts per Year

The number of refereed papers based on HST data is given in Figure 1 as a function of the year of publication. Hubble is an extremely productive telescope: between its launch in 1990 April and the end of 2003, it has produced data directly used in 4116 refereed papers. Following a strong and regular increase of publications during the first 8 yr, the number of papers continued to increase, although at a slower pace, during the last 5 yr, reaching a total of 502 for the year 2003.

The percentage of HST papers published in the aforemen-

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2 See http://archive.stsci.edu/hst/search.php.

3 See http://adsabs.harvard.edu.
tioned five major journals has grown from 1% in 1991 to 7% in 2003. Some special issues of the Astrophysical Journal have been dedicated to HST papers only: the first such issue was published in 1991 March with data from the first generation of instruments, while the last such issue, devoted to papers based on data from the Advanced Camera for Surveys (ACS), appeared in 2004 January (the papers in the latter issue are not included in this study).

Fourteen years after its launch, HST continues to show an increasing productivity, which can be explained by the regular servicing missions that maintain state-of-the-art technology for its scientific instruments and spacecraft systems. The rate of production of refereed papers reflects the increase in the “discovery space” provided by the new scientific instruments deployed in each servicing mission.

3.2. Paper Counts per Cycle

The numbers of refereed papers published per year for all the programs of a given cycle provide an interesting metric. Figure 2 presents such information for Cycles 1–2, 3–4, 5–6, and 7–8.

In Cycles 1–2 (top left panel), the initial increase in productivity during the first 3–4 yr culminates in a peak, which is followed by a slow decrease. Then the productivity stabilizes at about 20–30 papers per year, 10–12 yr after the beginning of these cycles.

There is an obvious major difference between Cycles 3 and 4 (top right panel). The high productivity of Cycle 4, when compared with Cycle 3, is a direct consequence of the first servicing mission, which corrected the spherical aberration of the primary mirror by installing new instruments. The significantly improved performance of HST triggered a burst in publications using the new, higher quality data.

This high level of scientific output has continued to increase since then, as shown in Figure 2 for Cycles 5–6 (bottom left panel) and for Cycles 7–8 (bottom right panel). Each cycle reaches a peak in productivity at about 180 papers approximately 3–4 yr after its beginning.

3.3. Paper Counts per Instrument

Figure 3 gives the number of refereed papers published per year based on data from each Hubble instrument. The number in each panel is the time integral of the corresponding curve. FGS stands for fine guidance sensors, FOC for Faint Object Camera, STIS for Space Telescope Infrared Spectrograph, GHRS for Goddard High Resolution Spectrograph, HSP for High Speed Photometer, NICMOS for Near-Infrared Camera and Multi-Object Spectrograph, FOS for Faint Object Spectrograph, WFPC and WFPC2 for the first and second Wide Field and Planetary Camera, and ACS for Advanced Camera for Surveys. The FOC, GHRS, HSP, FOS, and WFPC are decommissioned instruments, while FGS, STIS, NICMOS, WFPC2, and the ACS are active. A paper may be counted more than once if the data it uses come from more than one instrument.
3.4. Archives as an Instrument

By definition, we consider an archival HST paper as any paper that simultaneously fulfills the following two conditions: (1) it is based on HST data retrieved from MAST, and (2) none of its authors are either PI’s or CoI’s (co-investigators) on any of the HST programs from which these data originate.

Software tools that can identify such papers have been developed only very recently. We currently have an estimate of the fraction of archival HST papers for only the years 2000 through 2003. Out of the 1870 HST papers published during these 4 yr, 654 are archival HST papers. This amounts to 34% of the HST papers (K. Levay & MAST team 2004, private communication).

3.5. Citation Counts per Year

To estimate the scientific impact of refereed papers based on HST data, we obtain from ADS the total number of citations for each paper in our databases.

ADS is well aware that its citation counts may suffer from some (small?) incompleteness. However, ADS constantly improves its products and represents the most reliable source of citations for papers published in the major astronomical journals. ADS has two essential advantages: is it available online and is free of charge. Each week we use a script provided by ADS that allows us to directly access the total number of citations for each paper in our databases.

The Institute for Scientific Information (ISI), which is based in Philadelphia, sells citation counts that, after a few checks, appear to be no more reliable than those from ADS. Sandqvist (2004) presents a few examples of large differences between ISI and ADS attributable to errors made by ISI. Stevens-Rayburn & Bouton (2003) also discuss disparities in citation counts for the two providers.

For Figure 4, we consider only papers in the five major journals (ApJ, AJ, A&A, MNRAS, and PASP), since other journals such as Nature and Science would bias our statistics with their numerous highly cited articles that are not related to astronomy. The histogram in Figure 4 displays the mean total number of citations of refereed HST papers as a function of years since publication. For the older papers, published between 7 and 12 yr ago, the mean total number of citations is about 40 per paper, and is smaller for more recently published papers. The solid line in this figure shows the mean total numbers of citations per paper that is larger (by at least 25%) than the average number of citations of all the astronomical papers.

Figure 5 shows that a few years after publication, only about 2% of the refereed HST papers have no citations, whereas about one quarter of all refereed papers in astronomy have no recorded citation in ADS.

These two figures show that the refereed HST papers have a scientific impact that is significantly above average.

3.6. Citation History

Citation counts allow us to study the evolution of paper citation rates as a function of the years following publication. With such metrics we can answer the following questions: How
fast is the growth in the citation rate? Is there a maximum citation rate? After how many years is this maximum reached? And how fast is the decline in the citation rate?

We have obtained the individual citations of the 4116 refereed HST papers, courtesy of ADS (M. Kurtz 2003, private communication). This amounts to a total of 64,141 citations. Figure 6 presents the average citation counts per paper as a function of the number of years since publication. The solid line is the average for the HST papers, while the dashed line is the average of all refereed papers in astronomy.

In both cases, after a sharp initial rise, the peak of the citation rate occurs approximately 2 yr after publication. HST refereed papers peak at an average of 5.9 citations per paper per year, while the peak reaches only 3.2 citations per paper per year for all refereed astronomical papers. Thereafter, the citation rate decreases linearly to about 2 citations per paper per year 8 yr after publication.

Crabtree & Bryson (2001, 2003) generated similar curves for papers produced from observations by the Canada-France-Hawaii Telescope (CFHT) and the United Kingdom Infrared Telescope (UKIRT). Their curves peak at about 4.0–4.5 citations per paper per year and display the same general shape (a sharp rise with a maximum reached after 2 yr, followed by a slow decline). Abt (1981) showed that for papers published in 1961, citations reach a maximum 5 yr after publication. The delay between publication date and the peak of citations has shortened since that time to an average of 2 yr. This may be a direct consequence of the strong increase in the spread of information over the last decade via the World Wide Web.

3.7. ADS 2000–2001 Reads of Papers

For each paper, each access through ADS generates a log entry, which is called a “read.” An independent and new way of measuring the readership of a paper is the number of “reads” it generates (Kurtz 2003). Michael Kurtz of ADS kindly provided us with data related to this new metric.

During the 2 years of 2000 and 2001, ADS recorded about 12 million reads for all astronomy papers, of which 10 million were related to refereed papers. At that time, the then 3113 HST refereed papers accumulated 533,362 reads during these 2 yr, corresponding to 5.3% of all reads of astronomy papers.

4. HIGH-IMPACT PAPERS

There is more than one way to identify papers that have a high scientific impact. An interesting metric is given by papers that have the largest numbers of citations; these are called high-impact papers (HIPs) by ISI. We adopt the ISI definition: a paper is a HIP if it belongs to the 200 most cited refereed papers published in a given year. ADS has the capacity to sort all papers by citation counts and publication dates. It is straightforward to use ADS to obtain the top 200 papers published in a given year.

We identify the HST refereed papers that have enough citations to be among the HIPs published in a given year. Figure 7 provides the percentage of HIPs based on HST data as a function of publication year. After a slow start in 1991, 1992, and 1993, the effects of the successful deployment of COSTAR and WFPC2 can be seen in the obvious impact of refereed papers.

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4 See http://www.isinet.com/rsg/hip.
between 1993 and 1994. Since 1994, Hubble has consistently generated about 8% of all HIPs.

We have extracted the HIPs for the years 1998, 1999, 2000, and 2001, and have studied these 800 papers in greater detail. Namely, for each paper, we used ADS to access the full text, then read the paper and identified it as either an observational or theoretical paper. Hereafter, we consider only observational papers. If there is more than one telescope providing the observations for a paper, the weight or percentage of the contribution coming from each facility is roughly estimated (e.g., 50% HST, 25% Keck, and 25% Chandra), and the citations of this paper are attributed to the facilities as a function of these percentages. In this way, the total number of citations related to the 200 HIPs in a given year is distributed among all telescopes/facilities that provided the data.

Table 1 gives the distribution of the citations of the 200 HIPs published in 1998 as a function of the most highly cited facilities (we display here only the 12 most cited ones), from HST to ESO, followed by the same distribution for the years 1999, 2000, and 2001, respectively. These tables show that HST publications have the highest impact for the years 1998, 1999, and 2000, with some strong challenges from Keck, SCUBA, and BOOMERANG, while the impact of new space observatories, like Chandra and XMM-Newton, is clearly visible in 2001.

Our results, although based on a different sample of HIPs, are consistent with the values found by Benn & Sánchez (2001): HST generates 11% of the total HIP citations in the years 1995 to 2001.

5. TOP 10 MOST PRODUCTIVE HST PROGRAMS

Since all 4116 HST refereed papers are linked in our databases to the programs that have generated the data, it is straightforward to identify those programs that are the most productive. Table 2 lists the 10 most productive HST programs, in decreasing numbers of related papers, beginning with the program type (col. [1]), the program ID (col. [2]), the PI’s last name (col. [3]), the title of the program (col. [4]), the number of papers generated (col. [5]), and the total number of citations to these papers (col. [6]).

It is worth noting that all program categories are presented in this table, which includes not only General Observer (GO) programs, but also Guaranteed Time Observer (GTO) programs, Parallel (PAR) programs, snapshot (SNAP) programs, and Director Discretionary time (DD) programs. This illustrates the usefulness of each of these program categories. Not surprisingly, the top program is the Hubble Deep Field (PI: R. Williams), which may have produced the most original, broadest impact, and farthest reaching HST scientific results yet.

6. TOP 10 MOST CITED REFEREED HST PUBLICATIONS

The same databases allow identification of the most cited refereed articles based on Hubble data. Table 3 lists the 10 most cited HST papers. Column (1) gives the name of the first author, column (2) the title of the paper, and column (3) the bibliographic reference of the paper. These papers are sorted by decreasing numbers of citations (col. [4]).

This list of publications contains only papers presenting new scientific results; we have not included instrumental/calibration papers.

### Table 1

| Telescope | Fraction of the Total |
|-----------|-----------------------|
| **1998**  |                       |
| HST       | 13.5                  |
| Keck      | 7.5                   |
| Kamiokande| 6.8                   |
| COBE      | 6.8                   |
| NOAO      | 7.1                   |
| ROSAT     | 5.3                   |
| SCUBA/JCMT| 4.7                   |
| ASCA      | 4.0                   |
| Hipparcos | 3.3                   |
| ESO       | 2.7                   |
| **1999**  |                       |
| HST       | 11.8                  |
| Keck      | 7.6                   |
| ROSAT     | 7.3                   |
| SCUBA/JCMT| 5.3                   |
| Kamiokande| 5.1                   |
| WHT       | 3.2                   |
| NOAO      | 3.1                   |
| ISO       | 2.8                   |
| ASCA      | 2.5                   |
| CGRO      | 2.4                   |
| **2000**  |                       |
| HST       | 12.6                  |
| Keck      | 11.5                  |
| Chandra   | 7.7                   |
| Boomerang | 5.8                   |
| ASCA      | 4.6                   |
| ESO       | 4.1                   |
| MAXIMA    | 3.8                   |
| ISO       | 3.4                   |
| ROSAT     | 3.4                   |
| FUSE      | 3.4                   |
| **2001**  |                       |
| Chandra   | 12.6                  |
| XMM-Newton| 11.9                  |
| Keck      | 9.6                   |
| HST       | 8.9                   |
| ESO       | 7.8                   |
| AAT       | 4.9                   |
| MAXIMA    | 4.0                   |
| NOAO      | 3.9                   |
| SDSS      | 3.6                   |
| ROSAT     | 2.3                   |
TABLE 2
Top 10 Most Productive Programs

| Program Type | Program ID | PI         | Title                                             | Papers | Citations |
|--------------|------------|------------|---------------------------------------------------|--------|-----------|
| GO/DD        | 6337       | Williams   | Hubble Deep Field                                 | 119    | 5232      |
| GO/PAR       | 5369       | Griffiths  | Medium Deep Survey                                | 88     | 2029      |
| GO           | 2424       | Bahcall    | Quasar Absorption Line Survey                     | 58     | 1953      |
| SNAP          | 2227       | Mould      | Determination of the Extragalactic Distance Scale  | 57     | 2469      |
| SNAP          | 5476       | Sparks     | 3CR Radio Galaxies                                | 57     | 719       |
| GTO          | 5236       | Westphal   | Nuclei of Nearly Normal Galaxies                  | 48     | 1973      |
| GO/DD        | 8058       | Williams   | Hubble Deep Field South                           | 48     | 772       |
| SNAP          | 5479       | Malkan     | Subarcsecond Structure of AGN                     | 45     | 485       |
| GO           | 2563       | Kirshner   | SINS The Supernova Intense Study                  | 40     | 524       |
| SNAP          | 7330       | Mulchaey   | The Fueling of Active Nuclei                      | 40     | 416       |

1 Large or multicycle programs may acquire different ID numbers when scheduled through more than one cycle.

7. CONCLUSION

The creation of effective links between the STScI and ADS databases containing information about all HST programs and all HST refereed papers and their citations provides us with a powerful and versatile way to obtain metrics for describing the efficiency, productivity, and scientific impact of the Hubble Space Telescope project.

This may certainly help the funding agencies and the various governing committees in the shaping of future of HST time allocation by making educated decisions. The evaluation of the present performance of space facilities such as HST, Chandra, and Spitzer will help to maximize the efficiency and scientific output of future projects, such as the James Webb Space Telescope (JWST).

This research has made extensive use of the NASA Astrophysics Data System Bibliographic services. We thank the ADS team and especially Michael Kurtz for providing us with numerous data about citations and reads of HST papers. We are grateful to STScI Librarian Sarah Stevens-Rayburn for her invaluable input. Many thanks to the MAST team at STScI, particularly Karen Levay, Paolo Padovani, and Sara Anderson, for storing and handling the data used in this study. We are also grateful to Tim de Zeeuw and Don York for useful comments.

TABLE 3
Top 10 Most Cited HST Papers

| First Author | Title                                             | Reference | Citations |
|--------------|---------------------------------------------------|-----------|-----------|
| Madau        | High-Redshift Galaxies in the Hubble Deep Field   | 1996, MNRAS, 283, 1388 | 701       |
| Williams     | The Hubble Deep Field                             | 1996, AJ, 112, 1335 | 586       |
| Magorrian    | The Demography of Massive Dark Objects            | 1998, AJ, 115, 2285 | 568       |
| Perlmutter   | Discovery of a Supernova Explosion                | 1998, Nature, 391, 51 | 397     |
| Gebhardt     | Black Hole Mass and Galaxy Velocity Dispersion    | 2000, ApJ, 539, L13 | 378       |
| Freedman     | Results from the HST Key Project to Measure H₂     | 2001, ApJ, 553, 47 | 370       |
| Freedman     | Distance to the Virgo Cluster Galaxy M100         | 1994, Nature, 371, 757 | 301     |
| Stetson      | The Center of the Core-Cusp Globular Cluster      | 1994, PASP, 106, 250 | 278       |
| Freedman     | The HST Extragalactic Distance Scale              | 1994, ApJ, 427, 628 | 271       |
| Lowenthal    | Keck Spectroscopy of z ~ 3 Galaxies in the HDF    | 1997, ApJ, 481, L673 | 271       |

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