The Most Frequently Cited Astronomical Papers Published During the Past Decade

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From the Institute for Scientific Information we obtained the list of the 100 astronomical papers published worldwide in 1988-1997 that received the highest numbers of citations in the same interval. We augmented it with citation counts in 1998. Because papers published late in that decade had less chance of being cited, we converted the order in the list to citations per year, although we do not make use of the positions within the list. Despite the bias for the earlier papers to be included in this list, we consider them representative of the highly-cited recent papers. The results are: (1) half of the papers concern extragalactic objects and cosmology while one-third concern stars; (2) the numbers of observational and theoretical (including reinterpretations of published data) papers are equal; (3) half of the papers are based on optical-region data and about one-sixth each on radio and X-ray data; (4) the first authors came from 16 different countries, indicating that the highly-cited astronomical research has become international; (5) of the 51 observational and instrumental papers, 47% are based on data from 13 spacecraft, 42% on data from 15 ground-based optical observatories, and 11% from six ground-based radio observatories; (6) among the 14 journals represented in this list, we found that 4.4% of the papers published in the Annual Reviews of Astronomy and Astrophysics papers were included, 2.2% of the ApJS papers, 1.4% of the *Nature* papers, and 0.2% of the papers in each of six other journals.

1 INTRODUCTION

Funding and staffing in astronomy depends upon our perception of the most active fields, so it is reasonable to determine whether the most successful recent papers support that perception. The funding and staffing should depend not just upon high numbers of published papers but also of those papers that show by their high citation counts that they contain the most fundamental results or the most useful results for other researchers. Abt (2000) showed that almost invariably, important or useful papers produce high citation counts.

The Institute for Scientific Information has compiled a list of the 100 papers in astronomy that were published in 1988-1997 and received the most citations in the same ten years. The list can be obtained by subscription fee from the Institute for Scientific Information, 3501 Market Street, Philadelphia, PA 19104. The papers were published in journals worldwide and cited worldwide. Note that this list refers only to journal papers and not to conference proceedings, theses. monographs, private publications, or other types of publication. While there are monographs, such as Peebles' (1993) ''Principles of Physical Cosmology'' that, at 351 citations in 1993-1998, would fall near the top of this list, a spot check indicates that other highly-cited monographs, atlases, and catalogs are rare and would not change significantly the statistics given below. The numbers of citations were augmented by adding data from the 1998 Science Citation Index. The total citations range from 1081 to 202 per paper in 11 years. The locations of papers in the 1988-1998 list relative to the 1988-1997 list differed by a mean of $\pm$ 8 places.

Of course papers published late in the 1988-1997 interval were at a disadvantage in that they could be cited during only a few years compared with papers published early in that decade. Because papers have very different rates of growth or decay of citations with time, we cannot extrapolate their citation counts to a full decade. That list is not ideal from a statistical viewpoint. One would prefer to have a list of papers published during one decade followed by citations in the next decade. However, the initial lag before publication and the time it takes to compile the Science Citation Indexes would then mean that the counts would refer to observations made as many as 25 or more years previous and would not represent the current situation. Only by having overlapping decades of publication and citation can we obtain results that refer to the recent decade.

One way to partially overcome the unfairness to papers published late in the decade is to order the list according to citations per year following publication. That has been done in Table 1. It still means that the papers published late in the 1988-1997 decade need to have more citations per year than some of the earlier papers in order to be included in the list. However, none of the following analyses of distributions by fields of research, techniques used, wavelength regions employed, affiliations of the leading authors, observatory sites used, or journals are prejudiced by that time difference. In addition, we will not employ location within the list in any of our analyses.

Table 1 is a listing of the most-cited papers in order of decreasing total citations per year, ranging from 180 to 20 citations per year. With numbers that large, self-citations are insignificant. The first column gives the last name of the first author, the second gives the reference, and the third is the paper title.

What can we learn from this set of highly-cited papers? I looked at each paper and classified it according to (1) field of research, (2) technique used, (3) wavelength region, (4) affiliation of the first author, (5) observatory where the data were obtained, and (6) journal where the paper was published.

TABLE 1. List of the 1988-1997 Astronomical Papers Most Frequently Cited in 1988-1998 and Arranged in Order of Decreasing Citations per Year

First Author	Reference	Title
Smoot	ApJ,396,L1,1992	Structure in the COBE Differential Microwave Radiometer First Year Maps
Landolt	AJ,104,340,1992	UBVRI Photometric Standard Stars in the Magnitude Range 11.5< V< 16.0 Around the Celestial Equator
Schaller	A&AS,96,269,1992	New Grids of Stellar Models from 0.8 to 120 M at Z=0.020 and Z=0.001
Tanaka	PASJ,46,L37,1994	The X-Ray Astronomy Satellite ASCA
Holtzman	PASP,107,1065,1995	The Photometric Performance and Calibration of WFPC2
Walker	ApJ,376,51,1991	Primordial Nucleosynthesis Redux
Antonucci	ARAA,31,473,1993	Unified Models for Active Galactic Nuclei and Quasars
Stark	ApJS,79,77,1992	The Bell Laboratories HI Survey
Edvardsson	A&A,275,101,1993	The Chemical Evolution of the Galactic Disk. I. Analysis and Results
Freedman	Nat.,371,757,1994	Distance to the Virgo Cluster Galaxy M100 from the Hubble Space Telescope Observations of Cepheids
Cardelli	ApJ,345,245,1989	The Relationship between Infrared, Optical, and Ultraviolet Extinction
Lyne	Nat.,369,127,1994	High Birth Velocities of Radio Pulsars
D'Antona	ApJS,90,467,1994	New Pre-Main-Sequence Tracks for M< 2.5M0 as Tests of Opacities and Convection Model
Taylor	ApJS,88,529,1993	Catalog of 558 Pulsars
Alcock	Nat.,365,621,1993	Possible Gravitational Microlensing of a Star in the Large Magellanic Cloud
Peacock	MNRAS,267,1020,94	Reconstructing the Linear Power Spectrum of Cosmological Mass Fluctuations
Rogers	ApJS,79,507,1992	Radiative Atomic Rosseland Mean Opacity Tables
White	Nat.,366,429,1993	The Baryon Content of Galaxy Clusters: A Challenge to Cosmological Orthodoxy
Taylor	ApJ,411,674,1993	Pulsar Distances and the Galactic Distribution of Free Electrons
Meegan	Nat.,355,143,1992	Spatial-Distribution of Gamma-Ray Bursts Observed by BATSE
Dickey	ARAA,28,215,1990	HI in the Galaxy
Beckwith	AJ,99,924,1990	A Survey for Circumstellar Disks Around Young Stellar Objects
Wright	ApJ,396,L13,1992	Anistropy Detected by the COBE Microwave Background-Radiation
Loveday	ApJ,390,338,1992	The Stromlo-APM Redshift Survey. I. The Luminosity Function and Space Density of Galaxies
Sanders	ApJ,325,74,1988	Ultraluminous Infrared Galaxies and the Origin of Quasars
Morton	ApJS,77,119,1991	Atomic Data for Resonance Absorption Lines. I. Wavelengths Logward of the Lyman Limit
White	MNRAS,262,1023,93	The Amplitude and Mass Fluctuations in the Universe
Barthel	ApJ,336,606,1989	Is Every Quasar Beamed?
Broadhurst	Nature,343,726,1990	Large-Scale Distribution of Galaxies at the Galactic Poles
Abell	ApJS,70,1,1989	A Catalog of Rich Clusters of Galaxies
Tyson	AJ,96,1,1988	Deep CCD Survey: Galaxy Luminosity and Color Evolution
Iglesias	ApJ,397,717,1992	Spin-Orbit Interaction Effects on the Rosseland Mean Opacity
Duquennoy	A&A,248,485,1991	Multiplicity Among Solar-Type Stars in the Solar Neighborhood. II. Distribution of the Orbital Elements in an Unbiased Sample
Wheeler	ARAA,27,279,1989	Abundance Ratios as a Function of Metallicity
Mathis	ARAA,28,37,1990	Interstellar Dust and Extinction
Stocke	ApJS,76,813,1991	The Einstein Observatory Extended Medium-Sensitivity Survey. II. The Optical Identifications
Tsuneta	Sol.Phys.,136,37,91	The Soft X-Ray Telescope for the Solar-A Mission
Lynden-Bell	ApJ,326,19,1988	Spectroscopy and Photometry of Elliptical Galaxies.V. Galaxy Streaming Toward the New Supergalactic Center
Bruzual	ApJ,405,538,1993	Spectral Evolution of Stellar Populations Using Isochrone Synthesis
Balbus	ApJ.376,214,1991	A Powerful Local Shear Instability in Weakly Magnetized Disks. I. Linear Analysis
Jacoby	PASP,104,599,1992	A Critical Review of Selected Techniques for Measuring Extragalactic Distances
Maddox	MNRAS,242,L43,90	Galaxy Correlations on Large Scales
Efstathiou	MNRAS,258,L1,1992	COBE Background-Radiation Anisotropies and Large-Scale Structure in the Universe
Geller	Sci.,246,897,1989	Mapping the Universe
Kennicutt	ApJ,344,685,1989	The Star Formation Law in Galactic Disks
Turner	MNRAS,240,833,89	The EXOSAT Spectral Survey of AGN
Saunders	Nat.,349,32,1991	The Density Field of the Local Universe
Gioia	ApJS,72,567,1990	The Einstein Observatory Extended Medium-Sensitivity Survey. I. X-Ray Data and Analysis
Tsyganenko	Plan.Sp.Sci.,37,5,89	A Magnetospheric Magnetic-Field Model with a Warped Tail Current Sheet
Pagel	MNRAS,255,325,92	The Primordial Helium Abundance from Observations of Extragalactic Regions
Hedin	JGR,96,1159,1991	Extension of the MSIS Thermosphere Model into the Middle and Lower Atmosphere
Davis	Nat.,359,393,1992	Large-Scale Structure in a Universe with Mixed Hot and Cold Dark Matter
Mather	ApJ,354,L37,1990	A Preliminary Measurement of the Cosmic Microwave Background Spectrum by the Cosmic Background Explorer (COBE) Satellite
Lasker	AJ,99,2019,1990	Guide Star Catalog. I. Astronomical Foundations and Imaging-Processing
Efstathiou	MNRAS,232,431,88	Analysis of a Complete Galaxy Redshift Survey. II. The Field-Galaxy Luminosity Function
Maeder	A&AS,76,411,1988	Tables of Evolutionary Star Models from 0.85 to 120 M with Overshooting and Mass Loss
Pounds	Nat.,344,132,1990	X-Ray Reflection from Cold Matter in the Nuclei of Active Galaxies
Lilly	ApJ,369,79,1991	A Deep Imaging and Spectroscopic Survey of Faint Galaxies
Taylor	ApJ,345,434,1989	Pulsar PSR 1913+16
Turner	PASJ,41,345,1989	The Large-Area Counter on Ginga
Heckman	ApJS,74,833,1990	On the Nature and Implications of Starburst-Driven Galactic Superwinds

TABLE 1. (continued)

First Author	Reference	Title
Allamandola	ApJS,71,733,1989	Interstellar Polycyclic Aromatic-Hydrocarbons: The Infrared-Emission Bands, the Excitation Mechanism, and the Astrophysical Implications
Strom	AJ,97,1451,1989	Circumstellar Material Associated with Solar-Type Pre-Main-Sequence Stars: A Possible Constraint on the Timescale for Planet Building
Clavel	ApJ,366,64,1991	Steps Toward Determination of the Size and Structure of the Broad-Line Region in Active Galactic Nuclei. I. An 8 Month Campaign of Monitoring NGC 5548 with IUE
George	MNRAS,249,352,91	X-Ray Reflection from Cold Matter in Active Galactic Nuclei and X-Ray Binaries
Broadhurst	MNRAS,235,827,88	The Durham Anglo-Australian Telescope Faint Galaxy Redshift Survey
Nagase	PASJ,41,1,1989	Accretion-Powered X-Ray Pulsars
Colless	MNRAS,244,408,90	The LDSS Deep Redshift Survey
van Dishoeck	ApJ,334,771,1988	The Photodissociation and Chemistry of Interstellar CO
Hernquist	ApJS,70,419,1989	TREESPH: A Unification of SPH with the Hierarchical Tree Method
Bertout	ApJ,330,350,1988	Accretion Disks Around T Tauri Stars
Faber	ApJS,69,763,1989	Spectroscopy and Photometry of Elliptical Galaxies. VI. Sample Selection and Data Summary
Maeder	A&A,210,155,1989	Grids of Evolutionary Models from 0.85M to 120M: Observational Tests of the Mass Limits
Lee	ApJ,350,155,1990	The Horizontal-Branch Stars in Globular Clusters. I. The Period-Shift Effect, the Luminosity of the Horizontal Branch, and the Age-Metallicity Relation
Efstathiou	Nat.,348,705,1990	The Cosmological Constant and Cold Dark Matter
Bessell	PASP,100,1134,1988	JHKLM Photometry: Standard Systems, Passbands, and Intrinsic Colors
Sanders	ApJ,347,29,1989	Continuum Energy Distributions of Quasars: Shapes and Origins
Maeder	A&AS,84,139,1990	Tables for Massive Star Evolution at Various Metallicities
Edge	MNRAS,245,559,90	An X-Ray Flux-Limited Sample of Clusters of Galaxies: Evidence for Evolution of the Luminosity Function
Fabbiano	ARAA,27,87,1989	X-Rays from Normal Galaxies
Puget	ARAA,27,161,1989	A New Component of the Interstellar Matter: Small Grains and Large Aromatic Molecules
Lightman	ApJ,335,57,1988	Effects of Cold Matter in Active Galactic Nuclei: A Broad Hump in the X-Ray Spectra
Herbst	ApJS,69,271,1989	Gas-Phase Production of Complex Hydrocarbons, Cyanopolyynes, and Related Compounds in Dense Interstellar Clouds
Howarth	ApJS,69,527,1989	The Stellar Winds of 203 Galactic O-Stars: A Quantitative Ultraviolet Survey
Boulanger	ApJ,330,964,1988	Diffuse Infrared Emission from the Galaxy. I. Solar Neighborhood
Woosley	ApJ,330,218,1988	SN 1987A After the Peak
Rice	ApJS,68,91,1988	A Catalog of IRAS Observations of Large Optical Galaxies
Massey	ApJ,328,315,1988	Spectrophotometric Standards
Arnett	ARAA,27,629,1989	Supernova 1987A
Efstathiou	MNRAS,235,715,88	Gravitational Clustering from Scale-Free Initial Conditions
Smith	Sci.,246,1422,1989	Voyager 2 at Neptune: Imaging Science Results
Strong	A&A,207,1,1988	The Radial Distribution of Galactic Gamma Rays. IV. The Whole Galaxy
van der Veen	A&A,194,125,1988	The IRAS 2-Color Diagram as a Tool for Studying Late Stages of Stellar Evolution
Bowen	ApJ,329,299,1988	Dynamical Modeling of Long-Period Variable Star Atmospheres
Bajtilik	ApJ,327,570,1988	Quasar Ionization of Lyman-alpha Clouds: The Proximity Effect, a Probe of the Ultraviolet Background at High Redshift
Hummer	ApJ,331,794,1988	The Equation of State for Stellar Envelopes. I. An Occupation Probability Formalism for the Truncation of Internal Partition Functions
Walter	AJ,96,297,1988	X-Ray Sources in Regions of Star Formation. III. Naked T Tauri Stars Associated with the Taurus-Auriga Complex
Stetson	AJ,96,909,1988	CCD Photometry of the Globular Cluster M92
van der Hucht	A&A,199,217,1988	The Galactic Distribution and Subtype Evolution of Wolf-Rayet Stars. III.
Pierce	ApJ,330,579,1988	Distances to the Virgo and Ursa Major Clusters and a Determination of H0

One additional comment should be made about the nature of these papers. We mentioned that citation counts measure either the importance of a paper or its usefulness. For instance, among the 1954 papers in the *ApJ* and *ApJS* considered by Abt (1996), the 15 receiving the most citations during 1955-1994 included nine that were fundamentally important and six that were primarily useful to other researchers. Among the 53 papers selected by senior astronomers to be some of the most important ones of the 20th century and included in the AAS Centennial Issue (Abt 1999), 46 were of fundamental importance, three were primarily useful, and four were a mixture (Abt 1999). Identifications, which are partly subjective, of the current list yield the results that 58 are of fundamental importance, 38 are primarily useful, and four are a mixture. Examples of useful papers are the 2nd-5th papers in Table 1. We conclude that highly-cited papers are either ones containing fundamental results or are ones that are very useful to other researchers.

2 THE RESULTS

2.1 Fields of Research

The fields of research of the top papers are distributed as shown in Table 2. The standard errors in this table and the others were calculated from the square roots of the numbers of papers divided by the total number of papers. The num-

TABLE 2. Distribution of Papers by Fields of Research

Field	Papers by Number	Papers by Percentage
Extragalactic and cosmology	47	49 ± 7%
Galactic and interstellar	10	10 ± 3
Stellar	35	36 ± 6
Solar	1	1 ± 1
Solar system or terrestrial	3	3 ± 2
Total	96	99

bers of papers do not add up to 100 because four of the papers employed equipment or techniques that were applicable to many different kinds of objects.

Notice that half of the papers concerned extragalactic objects or cosmology and one-third concerned stars. It should be remarked that a small field, such as solar physics, that has few researchers is unlikely to produce a highly-cited paper unless it has applications to other fields, such as stellar astronomy.

2.2 Techniques

The papers were classified as to whether they were observational (containing new data), theoretical, or instrumental, Papers that did not contain significant amounts of new data but that were concerned primarily with the analysis or reinterpretation of published data were included among the theoretical papers. A few papers were attributed half to new observations and half to theory. The distribution is given in Table 3.

Notice that about half these most-cited papers are observational and half theoretical. That is consistent with the trend (Abt 1981) from 5% theoretical papers early in the 20th century to roughly half today.

2.3 Wavelength Regions

The distribution by wavelength regions is given in Table 4. In these assignments there were many papers (17%) that had to be credited partially to 2-5 different regions. That caused non-integral numbers of papers. There were 19 papers that were not attributable to any individual wavelength regions, such as papers on nucleosynthesis, stellar and terrestrial models, characteristics of disks, and numerical codes. A total of 81 papers could be classified by wavelength region.

We see that half of the highly-cited papers concerned the optical region, one-sixth each to the radio and X-ray regions, and the other sixth to the remainder (gamma rays, ultraviolet, and infrared combined).

TABLE 3. Distribution by Techniques

Technique	Papers by Number	Papers by Percentage
Observational (new data)	47	47 ± 7
Theoretical or reinterpretation	49	49 ± 7
Instrumental	4	4 ± 2

TABLE 4. Distribution by Wavelength Regions

Wavelength region	Papers by Number	Papers by Percentage
Gamma rays	2.00	3 ± 2
X-rays	10.92	14 ± 4
Ultravioleti	5.91	7 ± 3
Optical	39.75	49 ± 8
Infrared	7.50	9 ± 3
Radio and microwave	14.92	18 ± 5
Total	81.00	100

2.4 Distribution by First-author Affiliations

It may or may not be fair to consider the affiliations of only the first author of each paper, but the main conclusion (the diversity of affiliations) would probably not be changed by including the affiliations of all the authors.

The main result is that the first authors of these outstanding papers came from 16 different countries. It is gratifying to see that outstanding astronomical research has become an international endeavor. The trend during the last three decades for a 1% per year increase in international collaborations (authors from two or more different countries per paper) in astronomical journals worldwide (Abt 1990) is further evidence of the international character of current astronomical research.

2.5 Observatory Facilities

For the 47 observational papers and four instrumental papers the distribution by observatory facilities employed is given in Table 5. These are grouped by space, ground-based optical, and ground-based radio observatories. For papers that depend upon more than one observatory, partial credit is given to each one; that explains the fractional totals. It should be mentioned that the publication time interval studied (1988-1997) did not allow inclusion of papers from the Keck telescopes and some other new equipment.

In summary we find that 47% of the papers were based on space data, 42% on ground-based optical data, and 11% upon ground-based radio data. Together these represent 34 locations for new observations. NOAO stands out among the optical locations in providing the data used for one-third (32%) of the optical papers. There are surprises and disappointments in this list, for instance in that the university telescopes did not produce the majority of the highly-cited papers or that the large radio arrays did not dominate among the highly-cited radio papers.

2.6 Distribution by Journals

The numbers of papers published in various journals are listed in Table 6. Fourteen journals are represented. It is not surprising that the *Astrophysical Journal (ApJ)* has the largest fraction of this list of top papers because it publishes about 40% of all the papers appearing in the top 10 journals. However, it would be more fair to determine for each journal the fraction of all the papers published that appeared in this list.

TABLE 5. Observatory Facilities Used for 51 Observational & Instrumental

	Papers
Space:	
COBE	4
IRAS	4
IUE	3
HST	2.5
EXOSAT	2
Ginga	2
ASCA	1
BATSE	1
COS-B	1
Einstein	1
SXT	1
Voyager 2	1
HUT	0.5
Total	24
Ground-based Optical:	
KPNO	3.95
UK Schmidt	3.5
CTIO	2.95
AAT	2.7
Mt. Hopkins	1.75
Lick	1.2
CFHT	1
Univ. Hawaii	1
Mt. Stromlo	1
ESO	0.5
Isaac Newton	0.5
McDonald	0.5
Palomar	0.5
Univ. Arizona	0.25
Las Campanas	0.2
Total	21.5
Ground-based Radio:	
Arecibo	1
Bell Labs	1
Max-Planck	1
Nuffield	1
Owens Valley	1
VLA	0.5
Total	5.5

We estimated the number of papers published in each journal during 1988-1997 by counting the numbers of papers published in January-March 1990 plus January-March 1995, and multiplying the total by 20. In *Nature* we counted only the astronomical papers published. In *Nature*, the *Annual Reviews of Astronomy and Astrophysics (ARAA)*, and the *Publications of the Astronomical Society of Japan (PASJ)*, we counted all the papers published in 1990 plus 1995, and multiplied by 5. The estimated total numbers of papers are listed in the third column of Table 6. Dividing the second column numbers by the third, we derive the percentage of the published papers that appeared in the list. This was not done for the last four journals where the numbers are not statistically significant.

TABLE 6. Journal Rankings

Journal	Number of Papers In the List	Estimated Papers in 1988-1997	Percentage
ApJ	29	18,040	0.2 ± 0.03
ApJS	14	1,060	2.2 ± 0.6
MNRAS	12	5,440	0.2 ± 0.1
Nature	10	720*	1.4 ± 0.4
AJ	8	4,140	0.2 ± 0.1
ARAA	7	160	4.4 ± 1.6
A&A	6	10,620	0.1 ± 0.02
A&AS	3	1,420	0.2 ± 0.1
PASJ	3	785	0.4 ± 0.2
PASP	3	1,520	0.2 ± 0.1
Science	2		
JGR-Sp.Sci.	1		
Plan. Sp. Sci.	1		
Solar Physics	1		
Total		43,905	

*Astronomical papers only.

We see that papers in the ARAA have the highest probability (4.4%) of being highly cited. That is a reasonable result because many authors find it more convenient to cite a review paper than the individual research papers. Second in this ordering is the ApJS at 2.2% and third is *Nature* (data from *Articles* and *Letters* were combined) at 1.4%. Then most of the remaining journals (*ApJ*, *MNRAS*, *AJ*, *A&AS*, *PASP*, and *PASJ*) have a probability of statistically 0.2%. *A&A* seems lower.

We are grateful to Dr. Eugene Garfield and David Pendlebury of the Institute for Scientific Information, the University of Arizona Science Library for the use of their Science Citation Index, and the Space Telescope Science Institute Library for information.

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