Spitzer Publication Statistics

E. Scire, Luisa Rebull, and Seppo Laine
IPAC, Mail Code 314-6, Caltech, 1200 E. California Blvd. Pasadena, CA 91125, USA; escire@ipac.caltech.edu
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Abstract

We present statistics on the number of refereed astronomy journal articles that used data from NASA’s Spitzer Space Telescope through the end of the calendar year 2020. We discuss the various types of science programs and science categories that were used to collect data during the mission and discuss how operational changes brought on by the depletion of cryogen in 2009 May, including the resulting budget cuts, impacted the publication rate. The post-cryogenic (warm) mission produced fewer papers than the cryogenic mission, but the percentage of the exposure time published did not appreciably change between the warm and cryogenic missions. This was mostly because in the warm mission the length of observations increased, so that each warm paper on average uses more data than the cryogenic papers. We also discuss the speed of publication, archival usage, and the tremendous efficacy of the Legacy and Exploration Science programs (large, coherent investigations), including the value of having well-advertised enhanced data products hosted in centralized archives. We also identify the observations that have been published the largest number of times, and sort them by a variety of metrics (including program type, instrument used, and observation length). Data that have the highest reuse rates in publications were taken early in the Spitzer mission, or belong to one of the large surveys (large either in number of objects, in number of hours observed, or in area covered on the sky). We also assess how often authors have cited the Spitzer fundamental papers or have correctly referenced the Spitzer data they used, finding that as many as 40% of papers have failed to cite the papers, and 15% have made it impossible to identify the data they used.

Unified Astronomy Thesaurus concepts: Infrared observatories (791); Observatories (1147); Space telescopes (1547); Surveys (1671); Astronomical reference materials (90); Astronomy databases (83)

1. Introduction

Most major observatories track the number of refereed journal articles that use data from the given observatory. These paper number counts are frequently used to measure the scientific impact of an observatory (throughout this article, the word “paper” is used to mean a refereed journal article). The major observatories have broken down their publication counts by various metrics in an attempt to better understand how the observatory data were published (e.g., the Chandra X-ray Observatory, Blecksmith et al. 2005 the Hubble Space Telescope, Meylan et al. 2004). Cross-observatory comparisons (e.g., Crabtree 2008; Abt 2012) have also been attempted. These previous attempts have discussed the difficulty of defining a meaningful metric that quantifies the scientific impact of an observatory. Rots et al. (2012) proposed publication metrics based on the speed of publication, the fraction of the total observing time published, and the overall archival usage. These metrics are less sensitive to observatory-specific factors, such as the number of years the observatory has operated, the number of potential data users, the amount of research funding available, the breadth of the research projects, the number of observations that the observatory can make within a year, and the uniqueness of the data.
have the highest data reuse rates. Finally, there is a discussion of the number of refereed journal articles produced per hour of data observed (hereafter “papers per hour of observation”) that compares the three Spitzer instruments, the observing program types and finally the observing program size and observation length.

The intent of this paper is to provide a coherent look at all the Spitzer publication statistics once the Spitzer project stopped counting publications in detail at the end of the mission (at the end of year 2020). Counting publications has been an ongoing project throughout the lifetime of the Spitzer mission and has been chronicled in conference proceedings. Scire et al. (2010) describes the design and implementation of the publications database, and presents some basic publication statistics. Since that time, the full text searches have been transitioned to use the Astrophysics Data System\(^1\) (ADS) full text search engine. Scire (2014) had an initial look at why the publication rates changed so drastically between the cryogenic and warm missions after four years of warm operations. They concluded that the data were being published and that the larger program sizes had not slowed the publication of the data, but the average number of hours per paper had increased 3.5× between the warm and cryogenic missions. Scire (2018) provided a more in-depth look at the time between when the data are available in the archive and when they are published. It examined the difference between plotting this as hours of data and by individual observations. Some of the charts included in that paper have been updated here in Section 4.2 with an additional three years of data. Scire et al. (2020) provides an in-depth look at which programs and science categories produced the most papers and had the highest papers per hour of data rate. All of these papers provide earlier versions of the count of the total number of Spitzer papers, the percent of the total exposure time published, archival usage, and other publication statistics. The current paper expands upon Scire et al. (2020) by adding the final publications data from the year 2020 (22% of the papers from that year were published after those reported in Scire et al. 2020), expanding the analysis presented in the earlier conference proceedings, and including new analysis of the number of papers per hour of data rate for the different program types, program sizes and observation lengths.

### 2. The Spitzer Mission

The Spitzer Space Telescope was an infrared space-based observatory that was launched on 2003 August 25 and decommissioned on 2020 January 30 (6002 days). The portion of the mission in which science data were taken was split into two phases. The cryogenic mission ran from 2003 December (after the end of the in-orbit checkout and science verification period) until the exhaustion of the liquid helium coolant in 2009 May (5.5 yr) during which all three of Spitzer’s instruments were active (IRAC, Multiband Imaging Photometer for Spitzer or MIPS: Rieke et al. 2004, and Infrared Spectrograph or IRS: Houck et al. 2004). After the cryogen was exhausted, the Spitzer Warm and Beyond missions (hereafter collectively referred to as the “warm mission”) ran from 2009 July until the decommissioning on 2020 January 30 (10.5 yr).

During the warm mission, the passive cooling on the telescope and instrument chamber was good enough to keep the spacecraft and telescope temperatures low enough for the operation of the two shortest wavelength (3.6 and 4.5 micron) channels of the IRAC instrument with essentially no loss in sensitivity (Carey et al. 2010). However, the temperatures were not cold enough to operate MIPS or IRS. With only one instrument warm mission operations were significantly different from the cryogenic operations. The change with the most impact was the reduction of the warm mission budget to less than one-third of that of the cryogenic mission budget, resulting also in the decrease of data analysis funding for observers. Due to these changes, larger observing programs that could span multiple years were allowed. With more time allocated to the larger programs, the number of programs approved in each cycle of proposals in the warm mission decreased (Storrie-Lombardi & Dodd 2010). Table 1 summarizes the main differences between the cryogenic and the warm missions.

Over the lifetime of the Spitzer mission the science observations fell into a variety of categories (Figure 1). The telescope and instrument primary investigators were allocated 20% of the available observing time for the first 2.5 yr of the science mission, and 15% thereafter until the end of the cryogenic mission, as part of the Guaranteed Time Observations (GTO) program. Director’s Discretionary Time (DDT) proposals were submitted on a rolling basis throughout the mission and were approved by the Spitzer Science Center Director. All other time on the telescope was solicited through calls for proposals to the general astronomical community and competed through a peer-review process (this includes all General Observations (GO) time, Legacy, Exploration Science, Frontier Legacy and Snapshot programs).\(^2\) The various program types and the changes the science program went through over the lifetime of the mission in response to the operating constraints are summarized below.\(^3\)

Conceived before the launch, the initial Legacy\(^4\) programs were large, coherent programs designed to execute early in the

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\(^1\) Astrophysics Data System; https://ui.adsabs.harvard.edu/.

\(^2\) For exact solicitations of observing time please see the Spitzer Call for Proposals for all Cycles at https://irsa.ipac.caltech.edu/data/SPITZER/docs/spitzermission/observingprograms/proposalcycles/callsforproposals/.

\(^3\) For more information on all the programs selected for the Spitzer mission and the observing logs see https://irsa.ipac.caltech.edu/data/SPITZER/docs/spitzermission/observingprograms/.

\(^4\) For a list of approved Spitzer Legacy programs and links to their abstracts and data products please see https://irsa.ipac.caltech.edu/data/SPITZER/docs/spitzermission/observingprograms/legacy/.
Table 1
Summary of the Differences between the Spitzer Cryogenic and Warm Missions

|                              | Cryogenic Mission                  | Warm Mission           |
|------------------------------|-----------------------------------|------------------------|
| # of programs per observing cycle | ∼300                              | ∼60                    |
| Largest program              | 868 hr                            | 5286 hr (0.6 yr)       |
| PIs                          | 747 scientists from 38 countries  | 335 scientists from 22 countries |
| Total Data Analysis Funding ($K) | 106560.1                          | 37701.6               |
|                              |                                   | (35% of cryogenic mission, spread over more hours of data) |
| Most common proprietary periods of science observations (% of total time observed) | 0 days: 29.4% | 0 days: 71.0% |
|                              | 90 days: 0.7%                     | 90 days: 5.9%         |
|                              | 365 days: 68.0%                   | 365 days: 20%         |
| Hours of Science Observations | MIPS 36534 hr                      | IRAC 81188 hr          |
| Instrument                   | 24, 70, 160 micron imaging, SED mode | 5.2 to 38 micron spectroscopy, 16 and 22 micron imaging |
| Wavelengths                  | 11717.9                           | 14909.8                |
|                              | 32.1% of the cryogenic mission    | 3.6, 4.5, 5.8, 8.0 micron imaging |
| Hours of science observations | 41.1 minutes                      | 9906.0                |
| % of hours of data taken     | 40.8% of the cryogenic mission    | 100% of the warm mission |
| Avg observation length       | 46.2 minutes                      | 34.0 minutes           |
| Number of hours in Legacy, Exploration Science, and Frontier Legacy (large or multi-cycle) programs | 3724.1 | 46.2 minutes |
| Number of hours in GO, GTO, DDT, Snapshot (one cycle) programs | 1436.0 | 3612.5 |
| Papers published that used data from this instrument as of 08 Feb 2020 | 7993.9 | 6293.5 |
| Average number of refereed journal articles per hour of data (see Section 4.4.1) | 4414 | 13473.8 |
|                              | 0.13                              | 1927                   |
|                              | 0.38                              | 4529                   |
|                              | 0.46                              | 1756                   |
|                              | for observations before cycle     | 12: 0.07               |

Note. Portions of this table are reproduced from Scire et al. (2020) with permission from the author.
mission in order to provide a lasting legacy value for the Spitzer mission even if it ended early. The data taken in the Legacy programs had no proprietary period, and the science teams were contracted to produce enhanced data products (mosaics and/or catalogs) quickly. These were subsequently served to the community by the Spitzer Science Center and IRSA (NASA/IPAC Infrared Science Archive). In the warm mission, the maximum program size was increased, and multi-year Exploration Science programs were introduced (similar to the Legacy programs, they had a minimum program size of 500 hr and would be executed over two years). Cycle 13 introduced Frontier Legacy programs, which were Exploration Science programs with even larger allocations (the minimum size for a Frontier Legacy program was 2000 hr of observing time). In total, 32 Legacy programs totaling 8691.4 hr were selected, with the largest program having 868 hr; 42 Exploration Science programs totaling 38412.4 hr and three Frontier Legacy programs totaling 8545.1 hr were selected. The largest Frontier Legacy program was allocated 5286 hr and took three years to complete, with the final observations occurring the week before decommissioning. There were almost as many hours in the three Frontier Legacy programs as in all the cryogenic Legacy programs combined. The data from the Frontier Legacy programs were taken late in the mission, and as of the start of 2020, no papers have yet been published from those data (which is not surprising: see Section 4.2 below). The large number of hours of observations of Legacy/Exploration Science/Frontier Legacy programs (Figure 1) means that in the cryogenic mission 29.4% of the hours of science observations had no proprietary period. In the warm mission this number increased to 71% (Table 1).

Spitzer was designed to operate with only one instrument at a time to simplify operations and provide more robust power and thermal margins, so the observations were organized into instrument campaigns of 1–2 weeks in length. Downlinks occurred once every ~12 hr. These two operational constraints, combined with the high proposal pressure and the small average allocation per observing program, broke up the GO time on Spitzer into many small programs.

Figure 1. The program types for the science observations taken during the Spitzer mission. The cryogenic mission ran from 2003 December to 2009 May, and the warm mission ran from 2009 July to 2020 January. Legacy and GTO programs were in the cryogenic mission only. Exploration Science, Frontier Legacy, and Snapshot programs were in the warm mission only. It took 2–3 yr to complete observations for the largest Exploration Science and Frontier Legacy programs. The dip in hours of science observations in 2009 was due to the IRAC Warm Instrument Characterization (IWIC) period between the cryogenic and warm missions. See section 2 for discussion.

5 https://irsa.ipac.caltech.edu
6 For a list of approved Exploration Science and Frontier Legacy programs and links to their abstracts and data products please see https://irsa.ipac.caltech.edu/data/SPITZER/docs/spitzermission/observingprograms/es/.
Cryogenic Spitzer also had GTO and DDT programs (Figure 1).

In the warm mission, only the two shortest wavelength channels on the IRAC instrument were operating. The reduced data volumes meant that the downlinking frequency (and the overall time spent downlinking) could be reduced. At the start of the warm mission downlinks typically occurred once every ~24 hr, and in the final years of the mission it was typical to have two to three days between downlinks. As less time was spent downlinking and swapping between instruments, there was an increase in the number of hours of observations per year (Figure 1). The change in the maximum program size led to a drop in the average number of observing programs per cycle from the cryogenic mission level of ~300 programs per cycle to ~60 programs per cycle in the warm mission (Table 1). In addition, it turned out that a large fraction of the science selected in the warm mission was time domain astronomy (e.g., exoplanet and brown dwarf light curves and exoplanet transit observations, or multi-epoch observations). The net effect of all these changes was that the warm mission had larger programs with more complicated constraints, some of which could span a few years. To help cope with the increasing complexity of scheduling the observations, the Spitzer project introduced a new program type. Snapshot programs were introduced in the second proposing cycle in the warm mission (Cycle 7), and had observations that were less than one hour in duration, with no constraints and low data volumes, and that allowed the science goals to be accomplished with only ~50% of the specified observations taken. They were designed to fill in holes around the heavily constrained exoplanet and other time series observations that dominated the warm mission.

The increase in DDT observations in 2014 (Figure 1) was due to the observations of the Frontier Fields (Soifer & Capak 2013a, 2013b, 2013c, 2013d, 2014a, 2014b). The Frontier Fields were a Spitzer and Hubble Space Telescope Director’s Discretionary Time program to produce deep fields of strong lensing galaxy clusters. At the end of the mission there were several small DDT proposal calls at regular intervals to fill the remaining observing time. The increase in GO time in 2019 took place in observing Cycle 14 that was limited to GO and Snapshot observations (there were no Exploration Science or Frontier Legacy programs solicited in that observing cycle).

In total, there were 2422 observing programs over the lifetime of the Spitzer mission, resulting in ~146,000 science observations and 31,630 calibration observations. During the cryogenic mission, 82% of all science time was available to the general community through competitive proposals; during the warm mission this fraction was 100%.

3. Publication Data Compilation

3.1. The Spitzer Bibliographical Database

Throughout the mission, the Spitzer Science Center maintained a bibliographical database of refereed journal articles in which data from the observatory was used directly (rather than citing another paper or papers where such an analysis was done). It included papers that used the enhanced data products produced by the Legacy and Exploration Science teams and hosted at IRSA. The first author of this article inspected every paper before adding it to the database.

All the numbers in this article were current as of 2021 February 08 (unless labeled otherwise) and include all the papers published through the end of the year 2020. At that time, the database contained 9304 papers, and there were 475,142 citations to those papers. The h-index was 248 (as calculated by ADS (using Hirsch’s h-index)). There were ~4400 unique first authors in those papers, and ~15,500 unique authors overall. In early 2021, the publications database grew at a rate of ~1.5 papers per day. For more information about the publications database, please see Scire et al. (2010) Scire (2014, 2018) and Scire et al. (2020).

3.1.1. Finding the Papers

To find every paper that used data from Spitzer, we primarily relied on full text searches in ADS that use the name of the observatory, instruments, Legacy, and/or Exploration Science programs as search keywords. ADS full text searches include the text of the acknowledgments section of papers and figure captions. In some cases, we also track those papers that cite certain Spitzer fundamental papers. Of the two methods, the full text search produces the best results, as it does not rely on authors to correctly cite fundamental papers. While the Spitzer Science Center requested that all authors who use Spitzer data include a standard acknowledgment statement, not all authors have complied. Figure 2 shows the fraction of papers that correctly cited one of the fundamental papers for the telescope, instrument, Legacy, and/or Exploration Science programs or uses the Spitzer acknowledgment statement, as a function of time since the beginning of the mission. It also includes data for the number of papers that used data from an instrument and also cited that instrument’s fundamental paper. Soon after the launch (in 2004) the number of papers that correctly cited the fundamental papers was almost 85%. Between 2004 and 2012

8 Originally at http://sohelp2.ipac.caltech.edu/bibsearch/, the database contents were moved to https://irsa.ipac.caltech.edu/bibdata/bibliography_table.html in fall 2021. They are also available by searching on the “Spitzer” bibgroup in ADS and limiting it to refereed articles.

9 Only papers that reference the original enhanced products produced by the Legacy/Exploration Science Team are included (and flagged in the bibliographical database as using the enhanced products rather than Spitzer Science Center pipeline data). If those enhanced products were then included in a next generation catalog (as often happens with extragalactic deep fields), papers that reference the next generation catalog are not included.
this number declined, and since 2012, an average of only 62% of papers that use data from Spitzer cited one of these fundamental papers or used the acknowledgment statement correctly. When an observatory is new, most of the data use is by the proposing observers, who are explicitly told in their funding contracts to cite the fundamental papers and to use the observatory acknowledgment statement. As the archival use starts to grow, it becomes the responsibility of the authors to seek out this information when using the data, and that explains why the correct citation rate falls. Of the three instrument fundamental papers, IRS data users most often cite the IRS fundamental paper—but only 53% of the time (Scire et al. 2020 see Section 4.4.1 for discussion). We urge all the authors using data from any facility to correctly cite fundamental papers and/or use acknowledgments in their papers. Lack of proper citations/acknowledgments is not a problem unique to Spitzer; see Chen et al. (2021).

Certain Legacy and Exploration Science programs have acronyms that are so common that they produce too many false hits in a full text search (e.g., SIMPLE: van Dokkum et al. 2005, SEDS: Fazio et al. 2008, etc.). For those programs, we checked every paper that cited the fundamental paper for those programs. We know that we are undercounting the number of papers that result from these programs, as the number of papers that cite the fundamental telescope and instrument papers is smaller than the number of papers based on the Spitzer telescope or the corresponding instruments (Figure 2 above and

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**Figure 2.** Blue line: Percentage of all papers that used data from Spitzer and that cited at least one of the telescope, instrument, Legacy, and/or Exploration Science fundamental papers or used the acknowledgment statement correctly. Since 2012, an average of 62% of papers that use data from Spitzer cited one of these items. Other lines, as shown: percentage of papers that use data from an instrument and also cite the instrument’s fundamental paper.

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**Table 2**

| Year                  | 2008     | 2020     |
|-----------------------|----------|----------|
| Exact match           | 77.6%    | 55.6%    |
| Pretty Good           | 9.9%     | 20.4%    |
| Bad: Linked to all the data authors had access to | 11.8%    | 18.5%    |
| Very Bad: unlinked    | 0.2%     | 1.5%     |
| Other                 | 0.5%     | 4.1%     |

**Note.** Most papers include enough information to identify the data used to a relatively high degree of confidence ("Exact match", "Pretty Good"). Approximately 15% of papers do not ("Bad", "Very Bad"). See the text for category descriptions. This table updates the data presented in Figure 2 in Scire et al. (2020). The final 22% of the papers from 2020 have been added to the totals here.
We conclude that future missions should come up with unique names for their fundamental programs so that an accurate publication tracking (even without citations) becomes feasible.

### 3.1.2. Data Matching

Each paper is matched to the data it uses by hand. Most papers include enough information to identify the data used to a relatively high degree of confidence, but approximately 15% of papers do not (Table 2). In those cases, the papers were linked to all the possible observations that could have been used or to no observations at all. This results in a slight inflation in the number of hours published in all the graphs that follow. We urge all authors to provide enough information in their papers to allow a unique identification of the data that were used (see also Chen et al. 2021).

Papers were categorized by how well the authors described the data used in them (Table 2). “Pretty Good” papers are ones where a search on the target returned a few (2–4) observations that could have been used, but the author did not provide enough information to narrow it down further. “Bad: linked to all data the authors had access to” category includes papers where the authors specified a target, but that target was observed many times throughout the mission, and it was not possible to narrow down which observation (or perhaps all of them) the author used, given the lack of information in the paper. In those cases, the paper was linked to all the possible observations to which the author had access to when the paper was written. The “Very Bad: Unlinked” category includes papers that definitely do use data from Spitzer but do not include even rudimentary information needed to identify the data used (a target list, which instrument was used, etc.). These papers are not matched to any data. “Other” papers reference an older paper when talking about which observations were used, so the match is only as good as the older paper. Table 2 only includes data from the years 2008 and 2020, because those are the only two years for which this classification is complete. As is the case with fundamental paper citations and acknowledgements above, authors’ data description accuracy is slipping with time.

### 4. Results and Discussion

#### 4.1. Number of Papers and Percentage of Exposure Time Published

Figure 3 shows a plot of the number of refereed journal articles that used Spitzer data as a function of time since the beginning of the Spitzer mission. The number of papers per year peaks in 2012 (744 papers), 2.5 yr after the cryogenic mission ended, and then begins to decline (to only 469 papers in 2020). Figure 2 in Crabtree (2008) shows the rate at which various new ground-based telescopes begin to produce papers and concludes that a “plateau in productivity is reached seven to eight years after the initial publications.” Spitzer reached a plateau in the number of papers five years after the initial publications, in 2009 and remained there through 2015. We believe the rapid increase in the number of Spitzer papers after launch was due to a combination of the well-funded GO and Legacy teams, and the large number of hours devoted to the Legacy programs, which had no proprietary period, early in the mission. The effects of archived, ready-to-use Legacy data products appear later than five years after launch (see Section 4.4.3 below). The warm mission reached a rate of ∼200 papers per year in 2015 and the rate has remained at that level. If the warm mission papers follow the same curve as the cryogenic ones, we would expect the publication rate to begin to drop in the year 2025 or 2026. We should note that 53% of the papers that use warm data also use cryogenic data. This is due to observers using the warm mission to expand sample sizes and area covered in surveys, as well as adding more epochs to time series. When they publish the new warm data, they also republish the old, cryogenic data.

Even though the telescope hardware remained the same and there was little loss in sensitivity in the two IRAC channels that remained operational in the warm mission, the number of papers produced from the observatory dropped from the cryogenic to the warm mission, despite the fact that the number of hours observed per year increased in the warm mission (Figure 1 and Table 1). Even though there are 2.2 times more hours of warm data than cryogenic data, there are significantly fewer warm mission papers. It should also be noted that after the cryogenic mission ended in 2009, the plateau of ∼700 papers per year lasted until 2015, so it took six to seven years for the number of cryogenic papers to begin a slow decline. For both the warm and cryogenic missions, it took approximately five years after the start of the mission for the number of papers being published to reach a steady state.

Even though there are not as many warm papers as cryogenic ones, by examining the percentage of exposure time published (Figure 4, Table 3), it can be clearly seen that the warm data are getting published and used in several different investigations. Rots et al. (2012) argued that a simple count of the number of refereed journal articles per year is not a good metric for comparing the productivity between observatories, and proposed that the percentage of the exposure time published was a better metric. When comparing the Spitzer cryogenic and warm missions, this becomes very evident—the percentage of the exposure time published did not drop in the warm mission.

Researchers were still using the data, just in very different ways than researchers did with the cryogenic data.

There are many related reasons that led to the decrease in the number of papers for Spitzer, and the sections that follow attempt to delve into the various reasons in an attempt to ascertain which ones are the most important in contributing to the decrease in the number of papers.
For Spitzer, approximately 10% of the cryogenic science data taken remain unpublished over a decade after the data were taken (Figure 4, Table 3). A similar percentage of unpublished data (10%) can be seen for the Chandra X-ray Observatory (Rots et al. 2012 Figure 5). Rots et al. also find that for Chandra “as much as 60% of all exposure time may eventually be presented in publications more than twice.” It might be advantageous for observatories to look into their unpublished data to try to determine why they remain unpublished, and to call attention to these unpublished data.

As the Spitzer publications became more archival and the data analysis funding granted to PIs decreased (Table 1), authors shifted to journals without author fees (such as the Monthly Notices of the Royal Astronomical Society; MNRAS). The share of all Spitzer papers published in MNRAS rose from 10.4% in 2009 (the final year of the cryogenic mission) to 28.0% in 2020 (the final year of the warm mission), while the share of the papers published in the Astrophysical Journal (ApJ) dropped from 56.1% to 32.2% over the same time period. Other major journals retained a relatively constant percentage of Spitzer papers over the same time frame.

### 4.2. Speed of Publication

A very important factor to consider when counting publications is the speed with which observers generate papers and transit the publications process. Any changes made to the mission profile will take time to propagate out into the publication statistics. For the Legacy and Exploration Science programs with hundreds or thousands of hours of data, there is also a lag introduced while the data are being acquired if the nature of the program is such that the intended science cannot be accomplished without all the data in hand. In Figure 5 we examine the time between when the data were observed and when they were published.

The mean time to the first publication of the data (Figure 5(a)) varies by instrument: data from the cryogenic IRAC instrument is published ~6 months faster than data from the MIPS and IRS instruments. Data from IRAC are considered easier to use and most closely resemble visual wavelength data.
with which many astronomers have experience with. Spectral data (IRS) require more data analysis and a deeper understanding of the physics involved, and far-infrared data from MIPS are generally nontrivial to reduce. During the cryogenic mission the three instruments operated in series, but during the warm mission only the IRAC instrument was operating. This meant that Warm IRAC was generating three times as many hours of data as any one of the cryogenic instruments in the same amount of time. In addition, the cryogenic instruments only operated for 5.5 yr and Warm IRAC operated for 10.5 yr. These two factors caused the Warm IRAC first publication curve to be much steeper than the Cryogenic IRAC, MIPS or IRS first publication curves, because it contained many more hours of data. Moreover, those warm IRAC data were very similar to the cryogenic IRAC data, so quite a bit of software was already written and ready to be used on the warm IRAC data as soon as it arrived on the ground.

There are several interesting things to note about the data as they are republished (Figure 5(b)).

When the data are still relatively new (years 0–6) the three cryogenic instruments trend together very closely. As the data age, cryogenic IRAC data are more heavily reused than MIPS and IRS data. This is most likely due to the fact that in the warm mission, only the IRAC instrument was operating, and observers were expanding sample sizes and getting more epochs of data. When they publish the warm mission

![Figure 4. Percentage of the exposure time published, grouped by the instrument (left-hand side) or the observing cycle (right-hand side). Most data get published at least once (though there is a natural delay between the observation and the publication), and a significant fraction gets published many times. These numbers were calculated by checking how many times an observation had been published, then normalizing by the observation duration. Cycles refer to how the observations were broken up in the operations database. GTO phase 1, Original Legacy Science and Cycle 1 together made up the first ~two years of the mission. All the program types, including GTO and Legacy, are included in the bars for Cycles 2 and up. At the time of writing of this article, the data taken in Cycles 12, 13 and 14 were still relatively new, and observers were still working on publishing these data. The last Cycle 11 observation occurred on 2017 July 4. A version of this figure was published as Figure 4 in Scire et al. (2020). Since then, the percentage of data published in Cycles 12, 13, and 14 has increased. The raw data for this plot are in Table 3.](image-url)
of interest. It is also common with the Spitzer Infrared Nearby Galaxy Survey (SINGS; Kennicutt et al. 2004) data; authors are far more likely to download a mosaic of one galaxy than to use the entire SINGS data set.

If a paper included a statement along the lines of “We downloaded the SCOSMOS catalog/mosaics from IRSA” and then referenced the Spitzer fundamental paper for that program (Sanders et al. 2007), then the paper was marked as “with whole catalog usage.” This is very common for extragalactic deep field surveys where most authors choose not to reduce the data themselves but rely upon catalogs/mosaics. If the authors instead cited a paper other than the Spitzer fundamental paper for that Legacy/Exploration Science program, then the paper was not included in the counts of Spitzer papers. Those cases are usually where someone incorporated the Spitzer catalog into a new catalog with additional data from another observatory. As such, the Spitzer data are no longer a primary source.

The number of hours of data published by papers that are using the entire catalog/mosaics from the Legacy/Exploration Science programs (Figure 5(c)) far exceeds any other usage of the data. When plotted by the hours of observation, this usage is dominated by the investigators who use the catalogs or mosaics from the extragalactic field surveys. For example, each paper that uses the cryogenic SCOSMOS catalog is essentially using 627 hr of data. (The non-extragalactic surveys are also

10 Bibliography of recent refereed papers using popular data sets at IRSA: https://irsa.ipac.caltech.edu/bibdata/bibliography_list.html.
Most of the papers that used data from Spitzer have been archival papers or used a mix of proprietary and archival data (Figure 7). An archival paper is determined by comparing the paper authors’ last names with the last names of people listed on the observing proposal for all the data are used in the paper. The existence of the enhanced products, their clear documentation, and the ease with which people can find and use them, have all greatly increased the value of these data. Observatories looking to increase the number of publications or to maximize the scientific use of the data products should encourage observers (especially of large, coherent projects) to deliver ready-to-use data back to a publicly available archive, such as IRSA.\footnote{https://irsa.ipac.caltech.edu/irsa-dataQA.html}

When compared with Chandra (Rots et al. 2012, Figures 1 and 3), the Spitzer curves in Figure 5 show similar shapes. They both show a ramp-up that takes ~2 yr to the first publication when the data are new, and a long tail of older data being republished.

In a plot of the time needed to publish, sorted by the observing cycle in which the data were taken (Figure 6(a)), the cryogenic mission Cycles 1–5 tend to trend together for the first 2–4 yr after the data were taken. With ~300 programs per observing cycle in the cryogenic mission, any observer who is slow to publish generally only has a small number of hours of data, which does not materially impact the shapes of the curve in Figure 6. With only ~60 programs per observing cycle in the warm mission, a single slow observer is much more likely to have a more significant fraction of the total time observed, and their delay can really impact the shape of the curve. The time needed to publish data from the warm mission is much more variable—this is most likely due to the increase in the program size and the decrease in the overall number of programs per observing cycle. A few programs with thousands of hours of data took two or three years to observe. In those programs, observers are unlikely to use the data taken early in the observing cycle until they have received all of their data. This introduces an additional lag in the publication of data from these very large programs.

As the data age, some data from some observing cycles are more heavily reused than other data. GTO Phase 1, Cycle 1 and the Original Legacy cycles all contained approximately the same number of hours of observations and were all observed at the same time at the beginning of mission (Figures 6(a) and (c)), but 16 yr later the data from the Original Legacy programs are republished at a much higher rate than the GTO and Cycle 1 data. See Scire et al. (2020) for an in depth discussion of this topic.

4.3. Archival Data Reuse

The entire catalog text includes those instances where the paper used the enhanced data products should encourage observers (especially of large, coherent projects) to deliver ready-to-use data back to a publicly available archive, such as IRSA. The bin size is 6 months. Panels (a) and (b) include breakdowns by the mission phase (cryogenic, warm) and by the instrument. (c) only includes the mission phase. Panel (a) is in some sense a zoom of (b) which is a zoom of (c). MIPS, IRS and Cryo IRAC together make up the All Cryo line and ceased operations in 2009 May (11.75 yr ago). Warm IRAC operated from 2009 July to 2020 January (11.5 yr ago to 1 yr ago). See Section 4.2 for discussion. A version of (a) and (b) appeared as Figures 3 and 4 of Scire (2018) They have been updated with an additional three years of publication data in this paper.
The decision pre-launch to have the Legacy programs with no proprietary period (29.4% of the cryogenic data had no proprietary period; Table 1) and to make available ready-to-use enhanced products led to a rapid increase in the number of papers using Legacy data early in the mission and increased the fraction of archival papers produced. The warm mission had ...

Figure 6. Time elapsed between when the data were released to the Spitzer archive, and all the publications of the data, sorted by the observing cycle for the (a) cryogenic and (b) warm missions. (c) Total number of hours of observations in each cycle. A few cycles were 1.5 or 2 yr cycles (6, 11, 13) with a shorter cycle starting one year into them (7, 12). The cryogenic mission had many small programs producing papers at a constant rate; the warm era has more large programs that do not publish until all of their observations have been taken. An earlier version of this figure in a different format appeared as Figure 6 of Scire (2018). It has been updated with an additional three years of observation and publication data in this paper.
even less proprietary data (71% of warm data had no proprietary period). It is very important to have a well-advertised and easy-to-use archive with good documentation; as a mission ages, a large fraction of the data usage comes from people unaffiliated with the original observing program. Meylan et al. (2004) calculated that 34% of Hubble papers were archival, based on a comparison of the paper authors with PIs (primary investigators) or CoIs (co-investigators) on the programs. Spitzer’s fraction of archival papers appears to be higher, perhaps due to the large amount of data with no proprietary period, although it would be interesting to see how Hubble’s archival fraction has changed since 2004.

Information about which program have the heaviest data usage rates has been previously published in Section 2.2 in Scire et al. (2020) and discussed at length there. In brief, Scire et al. (2020) found that the programs with the heaviest data reuse rate when calculated by the number of hours published divided by the number of hours observed tend to be dominated by the Legacy or Exploration Science surveys of extragalactic survey fields (SCOSMOS: Sanders et al. 2005 and Sanders et al. 2006, GOODS: Dickinson et al. 2004, etc.). This is due to the fact that when authors use the extragalactic survey field data, they use all of it at once to reach the required depth. Other fields on the sky that have large numbers of hours published relative to the number of hours observed are the galactic plane (Churchwell et al. 2004 and Churchwell et al. 2005; Benjamin et al. 2006; Carey et al. 2006), the Large and Small Magellanic clouds (Meixner et al. 2005 and Gordon et al. 2007) and three star-forming regions (Evans et al. 2004). However, if one plotted the programs that have the largest number of papers (Scire et al. 2020 Figure 6), then the shallower surveys of many astrophysical objects dominate, with GLIMPSE I (Churchwell et al. 2004) and the Spitzer Infrared Nearby Galaxy Survey (SINGS; Kennicutt et al. 2004) producing the most papers. In addition, some Guaranteed Time Observer (GTO) programs have extremely large numbers of per hour of observation rate because the GTO programs selected their targets first before the launch. That had the effect of concentrating many of the interesting and easy observations of small fields into GTO Phase I.

4.4. Number of Published Papers per Hour of Observation

Here we address the number of published papers per hour of observation broken down by the instrument, the observing program category (with special attention paid to the Legacy and Exploration Science Programs) and the program allocation and average observation length. For information about the papers per hour of observation rate for the various science categories, see Section 2.4 in Scire et al. (2020).
Figure 7. Archival Spitzer papers. To calculate this, the last names of the paper’s authors were compared to the last names of all the people on an observing proposal. An archival paper is one where no authors match anybody on the proposal. A non-archival paper has at least one match for all the programs used in the paper. Papers classified as both use data from multiple programs and have at least one program that is archival, and one program that is non-archival. This graph does not take into account the amount of time that has passed between an observation was taken and when it was published. An earlier version of this figure appeared as Figure 10 in Scire (2018). It has been updated with an additional three years of publication data here.

Figure 8. Total number of Spitzer papers by instrument. MIPS and IRS were decommissioned in 2009 May and IRAC in 2020 January. A version of this figure was published as Figure 7 in Scire et al. (2020). Data from 2020 have been added to the plot shown here.
4.4.2. Program Types

Blecksmith et al. 2005 found that for Chandra, the GTO programs regularly produced more papers per kilosecond of observations than the GO programs and attributed it to the fact that GTO observers work in large teams, while GO observers tend to be one or two people. This is true for Spitzer as well, but we believe there are additional contributing factors to the differing rates for Spitzer (Figure 9). Before the launch, the Legacy and GTO programs were selected before the GO programs. Because they were selecting targets first, the high-value, easy to observe, very popular fields ended up clustered in the Legacy and GTO programs (with the Legacy programs covering the large fields and the GTO programs covering the small ones). In addition, the Legacy and GTO programs were funded over a span of years, allowing the teams to have a dedicated stable workforce. They also received data analysis funding that was at a higher level than most of the GO programs. All of these factors can help to explain why the papers per hour of observation rate is smaller for the GO programs in the cryogenic mission.

The highest rate of papers produced per hour of data obtained is found for the cryogenic DDT programs. The DDT programs were submitted on a rolling basis throughout the cryogenic and warm missions for emerging science (high risk/high reward) or unanticipated time critical observations. These observations tended to be of exciting events, and were given a proprietary period of at most 90 days. Both of these factors may help explain why they have a higher papers per hour of data rate, but it may also be a function of the small sample size. In total, only 3.3% (1261 hours) of the observed science time in the cryogenic mission was in DDT observations. The rest of the time was in Legacy programs (24.0%), GTOs (17.8%) and the GO programs (54.7%).

For the warm mission, the number of papers per hour of observation rate is significantly lower than the cryogenic mission rates. In particular the rate for the Exploration Science programs is lower, due largely to the nature of the science that warm IRAC was good at doing. With only one instrument operating with two channels, 3.6 and 4.5 microns, it turned out that most of the science selected was extragalactic surveys, extrasolar planet transit/eclipse light curves, extrasolar planet and brown dwarf phase curves and other time series observations (Scire et al. 2020 Figure 8). These kinds of science require a greater time investment for science returns (for example, hundreds of hours invested in a time series may only produce one paper.) Also, in the warm mission, more time was devoted to large Exploration Science surveys, which reduced the number of GO programs (Figure 1). See below (Figures 11 and 12) for a breakdown of how the average observation length and the total time observed impact the papers per hour of observation rate.

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Figure 9. Papers per hour of observation rates sorted by program types for the cryogenic and warm missions. GTO and Legacy programs were cryogenic mission only, and Exploration Science and Snapshot programs were warm mission only. The warm mission only includes data for observing cycles <12 because later cycles are still in the process of producing their initial papers (Figure 4). See Figure 1 for a breakdown of program types and number of hours of observations in each category. See Section 4.4.2 for discussion.

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12 Cryogenic GO programs were funded according to a formula that was instrument dependent. IRAC observations were funded at a lower level than IRS and MIPS observations, and the mix of instruments used could result in GO funding levels that were higher on a dollars/hour of observation rate than the GTO/Legacy programs, but frequently were not.
The DDT observations in the warm mission did not produce a higher papers per hour of data rate, unlike the cryogenic DDT observations. The warm mission DDT observations do not suffer from as much of a small sample size problem: 9.2% (7791.3 hr) of the observed time in the warm mission was in DDT observations. The average amount of observing time in a cryogenic DDT program was 8.5 hr, while for the warm DDT programs it was 39.6 hr. 62% of the warm DDT time went to programs with more than 100 hr of observations, whereas the largest cryogenic DDT program was allocated 59.3 hr.

4.4.3. Legacy/Exploration Science Data Usage

The first Legacy program enhanced data products were released in October of 2004, yet the number of papers using these data only grew slowly until 2010, when their usage starts to accelerate (Figure 10). Since it takes 1–3 yr for data to be published after the authors have access to them (Figure 5) that means there was an additional, significant lag in usage of the enhanced data products. It may be that it took time for astronomers to learn of these products and for their confidence in the products to grow enough for them to be preferred over the pipeline products from the Spitzer Science Center pipelines or their own reductions. They also could have been better advertised. In email blasters sent to the astronomical community, the Legacy enhanced products were mentioned two times in total before 2008. In 2008 they were mentioned three times, in 2009 nine times and after 2009 there were regular mentions 4+ times a year. They were also initially only available from a special website that was separate from the rest of the data archive, so the data users had to know to go look for them. As time progressed, they were better integrated into the rest of the archival interfaces at the Spitzer Science Center and IRSA, which has helped their popularity to grow.

To encourage the use of enhanced data products, we suggest that they be placed in a well-advertised and maintained archive, and that the astronomical community be reminded of their existence on a regular basis. We also recommend they be integrated into object search engines (e.g., NASA/IPAC Extragalactic Database (https://ned.ipac.caltech.edu/, etc.) where possible.

4.4.4. Program and Observation Length

In Figures 11 and 12, each of the points on a graph are for one Program ID (PID). A few observing programs (Original Legacy Science, and Exploration Science programs, and microlensing programs) were split across multiple PIDs to make bookkeeping for the program easier (e.g., SWIRE (Lonsdale et al. 2004) was split by the field on the sky, the Carnegie Hubble Program (Freedman et al. 2008) was split by the target type, and microlensing (Gould et al. 2014) was split by the week observed). Only PIDs where >75% of the hours of observations were completed are included (1573 cryogenic
PIDs and 507 warm PIDs. A total of 91 PIDs were excluded; 45 of the excluded PIDs were Cycle 5 priority 3 programs that were not completed before the cryogen was exhausted. The cryogenic depletion date was somewhat unknown, so enough science was selected to fill the time to the latest possible date, with the priority 1 and 2 science scheduled before the priority 3 science. The warm mission Cycles 12–14 have been omitted from these graphs because the data are still fairly new, and observers are still working on the first publications (see Figure 4).

By looking at Figures 11 and 12, it is clear that PIDs with large numbers of papers per hour of observation rates tend to have modest allocations (<1 hr) with short individual observations. Longer observations tend to produce fewer papers per hour of observation. For Spitzer, most of the long (>5 hr) observations were exoplanet transit or eclipse and exoplanet and brown dwarf phase curve measurements. There was a 24 hr limit on an observation’s duration, and so frequently for these measurements several long observations were strung together in a row to produce longer data sets. (The longest continuous phase curve observed was 87 hr broken into 4 observations chained together, and the longest observations were 21 and 22 days with breaks only for downlinks and spacecraft calibrations.)

Surprisingly, the average observation length for the entire cryogenic mission is almost identical to that of the entire warm mission: 48.2 minutes and 48.1 minutes, respectively. However, the standard deviation of the observation length is very different for the two mission phases: the cryogenic mission had a standard deviation of 64.6 minutes, while for the warm mission it is 113.9 minutes.

We would like to explicitly point out that the observations that produced the highest papers per hour of data rate were of specific, very popular areas of the sky (for more information on which areas of the sky see Scire et al. 2020). We believe that it is beneficial to the community to make sure that those areas of the sky are observed by most observatories and the data be put into a well-advertised and maintained archive. It is also apparent in Figures 11 and 12 that just because a program has a modest allocation or short observations, it does not necessarily produce a higher papers per hour of data rate. In fact, for the cryogenic mission the programs with the highest allocation (the Legacy programs) have middling rates of papers per hour of data (Figure 12(b)) that are continuing to increase at rates exceeding that of the smaller programs. Comparing the large cryogenic program to the warm programs of similar allocation (Figure 12(a)), the cryogenic programs have higher papers per hour of data rates. This may be because the cryogenic data are older and have had more time to be republished, or it may be

![Figure 11. The average observation length vs. the number of refereed journal articles per hour of data observed for that PID. The horizontal axis is logarithmic. (a) all Spitzer PIDs for all the observing cycles before Cycle 12, (b) just the cryogenic mission (c) just the warm mission for programs before Cycle 12. The scale of the axes on all the three graphs is different. PIDs with a very large papers per hour of observation rates tend to have modest allocations (<1 hr) with short individual observations.](image.jpg)
because the most useful fields on the sky were observed earlier in the mission. Counting papers with this level of detail for another $\sim 10$ yr would answer this question, however there is no funding to do so.

5. Summary

The cryogenic and warm Spitzer missions had very different rates of publication in refereed journals. After the cryogen was exhausted in 2009 May, only half of the IRAC instrument remained operational, and the number of programs approved in each roughly annual observing cycle decreased from $\sim 300$ to $\sim 60$. At the same time, the overall budget for the mission (including the data analysis funding distributed to the observers) was reduced. The types of science that best suited the warm IRAC instrument tended to have substantially longer individual observations than those made in the cryogenic mission. All these factors combined led to a reduction in the number of papers that were published annually in the warm mission. However, the fraction of Spitzer observing time that was published and re-published did not substantially change between the cryogenic and warm missions. The total numbers of papers from each of the cryogenic and the warm mission do not capture the complexity of what factors affected the publication rate in each phase of the Spitzer Mission, so raw paper counts are not good metrics for the “success” of an observatory.

Because the publication rates between the warm and cryogenic missions differ so greatly, we find that for Spitzer we have to be careful when comparing the publications from the same observatory since the mission profile changed significantly between the warm and cryogenic missions. This also suggests that more care needs to be taken when doing cross-observatory comparisons based on raw counts of paper numbers. We encourage more observatories to consider the fraction of observing time published as a most robust metric, even though it does require more resources to calculate.

Most of the time there is a delay of one to four years between the time when the data are taken, and the time when results from these data are published for the first time. This delay depends on the instrument the data were taken with. The simpler IRAC data were on average published six months faster than the data from the instruments that required more resources.
processing (MIPS, IRS). Also, the data from Spitzer’s two imaging instruments (IRAC and MIPS) can often be used in multiple, often independent research projects, and therefore result in multiple papers. Data from the spectrograph (IRS) often are taken for a single, targeted object, and therefore are less amenable to be used in large surveys that cover huge swaths of the sky (and that often produce many papers).

The absence of proprietary periods for data contained in several large programs led to a quick upturn in the number of papers that used Spitzer data at the start of the mission. Ready-to-use (reduced) data that are stored in a well-advertised, well-organized, well-documented, and freely accessible data archive have contributed to the publication of a large number of archival papers that often use the same data sets multiple times. The enhanced data products from the Legacy and Exploration Science Teams have been very heavily used, and the number of hours of data published by papers that are using the entire catalog/mosaics from the Legacy/Exploration Science programs far exceeds any other usage of the data. However, it took some time for these teams to make their products available and make other researchers aware of the value of these data. A large fraction of Spitzer papers use data from a small fraction of all the executed observing programs, specifically utilizing the Legacy, GTO, or Exploration Science programs. The original Legacy and GTO programs were given target selection priority before the launch. For this reason, many of the interesting and most obvious targets were included in those programs, and those data are frequently re-used.

A long operational lifetime of an observatory and/or an instrument allows observers to expand their sample sizes and to acquire new epochs of observations, producing more publications and increasing the reuse of the archival data.

Smaller program allocations produce many papers very soon after observation, whereas the larger programs result in a longer ramp up time but have a longer, more robust publications tail. For Spitzer, the mix of small and large programs in the cryogenic mission produced swift upslopes in the number of papers produced and a robust long term publication rate and data sets that are still in heavy use over a decade after the cryogenic mission completed.

The changes made for the warm mission allowed for a new investigative parameter space and allowed observers to answer questions that require significantly more investment of observing time. While the paper counts may be lower, the warm mission allowed significantly more exoplanet light curves to be taken with much longer durations, provided confirmation observations for Kepler (Koch et al. 2010) and TESS (Ricker et al. 2015), helped refine the Hubble Constant, assisted in the discovery of the seven Earth sized planets orbiting TRAPPIST-1 (Gillon et al. 2016), inspired a Google Doodle and a front page of the New York Times (above the fold) (Chang 2017), and then spent hundreds of hours studying the TRAPPIST-1 system to make it the best categorized solar system outside our own.

Finally, we urge authors of journal papers to cite the observatory fundamental papers, and to provide enough information in their publications to allow a unique identification of the data that were used. We also urge observatories and observers to pick names for their observing programs that are unique enough to allow a full-text search and to identify the relevant results easily. Since 2012, only 62% of papers that used data from Spitzer cited either the fundamental papers or the observatory acknowledgement statement. About 15% of the papers did not supply enough information to uniquely identify the Spitzer data used in the publication. Given the time delay from data taking to the publication of the results, and the huge program sizes and resulting data sets that were taken toward the end of the Spitzer mission, and if funding existed, it would be interesting to count Spitzer papers with the same careful analysis five to seven years after the end of the mission to determine what has happened to the Spitzer warm mission data publication rates.

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**ORCID iDs**

E. Scire  [https://orcid.org/0000-0003-1468-5357](https://orcid.org/0000-0003-1468-5357)

Luisa Rebull  [https://orcid.org/0000-0001-6381-515X](https://orcid.org/0000-0001-6381-515X)

Seppo Laine  [https://orcid.org/0000-0003-1250-8314](https://orcid.org/0000-0003-1250-8314)

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