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The Bolocam Galactic Plane Survey

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Abstract. The Bolocam Galactic Plane Survey (BGPS) is a 1.1 mm continuum survey of the northern Galactic Plane made with Bolocam and the Caltech Submillimeter Observatory. The coverage totals 170 square degrees, comprised of a contiguous range from $-10.5° \leq l \leq 90.5°$, $-0.5° \leq b \leq 0.5°$, with extended coverage in b in selected regions, and four targeted regions in the outer Galaxy, including: IC1396, toward the Perseus arm at $l \approx 111°$, W3/4/5, and Gem OB1. Depths of the maps range from 30 to 60 mJy beam^{-1}. Approximately 8,400 sources were detected and the maps and source catalog have been made publicly available. Millimeter-wave thermal dust emission reveals dense regions within molecular clouds, thus the BGPS serves as a database for studies of the dense interstellar medium and star formation within the Milky Way.

1 Introduction

Millimeter-wavelength continuum surveys provide a very efficient means for detecting cold, dense regions within molecular clouds via their (optically thin)

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thermal dust emission. In recent years, the advent of large-format bolometer-array cameras has enabled unbiased, large-scale surveys of molecular cloud complexes essential for the determination of the intial conditions of star and cluster formation and the characterization of the sites of ongoing star birth. As an example, Enoch et al. (2007, 2008) mapped 19 square degrees in the Perseus, Rho Ophiuchus, and Serpens molecular clouds, cumulatively detecting 201 cores and deriving and intercomparing their core mass functions.

After we commissioned Bolocam and routine observations were underway, based on Bolocam's mapping speed Tom Phillips recommended that we consider a survey of the northern Galactic Plane, suggesting that we'd detect thousands of sites of dust emission (quite rightly: we have detected 8,440 sources!). Such a global survey, when combined with distance estimates from spectroscopy, allows for systematic studies of star formation as a function of environment. Properties such as mean clump sizes, masses, and luminosities can be measured and used to test models of cloud structure and evolution and used to inform extragalactic observations where individual cloud clumps cannot be resolved.

Similar submillimeter surveys have been undertaken or are underway: The ATLASGAL project will map 360 square degrees of the Plane visible from the Southern Hemisphere at 870 μm with the APEX telescope (Schuller et al. 2009) the *Herschel Space Observatory* Hi-GAL project will map the inner $\pm 60°$ portion of the plane of the Milky Way at 250, 350, and 520 μm beginning in 2010. Both surveys will overlap substantially with the BGPS, allowing for spectral energy distributions, and hence dust temperatures, luminosities, and masses, to be derived for thousands of sources. Together, these surveys will form a database for detailed studies with ALMA.

2 Observations and Data Reduction

Bolocam is a facility-class millimeter-wave camera at the CSO, with observing bands at wavelengths of 1.1 and 2.1 mm (http://www.cso.caltech.edu/bolocam/), and a $7.5'$ field of view (Glenn et al. 2003). The heart of Bolocam is a focal plane array of 144 ac-biased silicon-nitride micromesh bolometers (of which 115 are in use), which are operated at 250 mK and which served as the precursor to the submillimeter bolometer focal plane arrays for SPIRE on the *Herschel*. The 1.1 mm band is centered at 268 GHz and has a bandwidth of $\Delta\nu/\nu = 0.17$; the net beamsize in the maps is $33''$ FWHM.

Observations were made in a raster scan mode (without chopping) in six observing runs spanning July 2005 to September 2007. The data were reduced using a custom pipeline that utilizes a principal component analysis and iterative mapping to remove sky noise while attempting to preserve astrophysical emission with high fidelity. Details of the pipeline, calibration, photometry, and astrometry are described in Aguirre et al. (2009), which is available on the data archive website.

3 Preliminary Results and Public Data Release

The BGPS maps are presented in Figures 1 through 9. A few things are immediately evident in the maps: First, millimeter-wave continuum emission is condensed, with a smaller areal filling factor than CO emission. Second, in addition to discrete sources there is extended filamentary emission, partially comprised of interconnections between individual sources. Third, "negative bowls" are present around the brightest sources. An extreme example of this is around Sgr B2 in the Galactic Center region (third panel of Fig. 1). These are artifacts of the sky subtraction algorithm, which is described in detail in Aguirre et al. (2009). Only photometry of faint emission surrounding bright sources is significantly affected.

A custom algorithm, Bolocat, was created to identify and extract sources in the BGPS maps based on their significance with respect to a local estimate of the noise in the maps. The algorithm and simulations characterizing its performance are described in Rosolowsky et al. (2009). For each extracted source, the coordinates, major and minor axis moments, position angle, and flux densities in 40 arcsecond, 80 arcsecond, 120 arcsecond, and source-size apertures (and associated uncertainties) are listed. The distribution of flux density in sources as a function of Galactic longitude and latitude are given in Figure 10, which shows the dense molecular gas is highly peaked in the center of the Galactic mid-Plane. 11.9 kJy of flux density is comprised by the sum of the flux densities of the sources in the catalog.

The flux density distribution of the sources follows a power law over nearly three orders of magnitude (Fig. 11). Note that the BGPS is *flux limited*, hence the power-law is not simply related to the source mass distribution. Rosolowsky et al. (2009) explore the physical nature of a subset of the BGPS sources near $l \sim 31^\circ$ using spectroscopic observations with the NH_3(1,1) inversion transition.

BGPS maps and the Bolocat catalog are maintained in a public archive for use by the community (http://irsa.ipac.caltech.edu/data/BOLOCAM_GPS/). FITS files can be downloaded, which include calibrated maps, maps of the integration time per pixel, and noise maps. Sky noise, instrument noise, and pipeline-induced artifacts all contribute to the noise maps. The catalog is object searchable and downloadable in whole and the site serves as an archive for documentation and rereleases.

Several follow-up studies of the BGPS are being undertaken by our collaboration, including a spectroscopy campaign to estimate distances to the sources using the Galactic rotation curve and to determine their physical characteristics. Dunham et al. (2009) present NH_3 (1,1) through (4,4) observations of 50 BGPS sources in the Gem OB1 region. Source masses are derived from the dust emission and virial masses are derived from the ammonia spectroscopy and dust emission, as well as physical densities and column densities. The data imply that the BGPS sources are "clumps" of the size from which stellar clusters form. Bally et al. (2009) have undertaken a comprehensive morphological study of the molecular gas in the Galacitic Center by combining the BGPS maps with infrared, submillimeter, and radio observations from the literature.

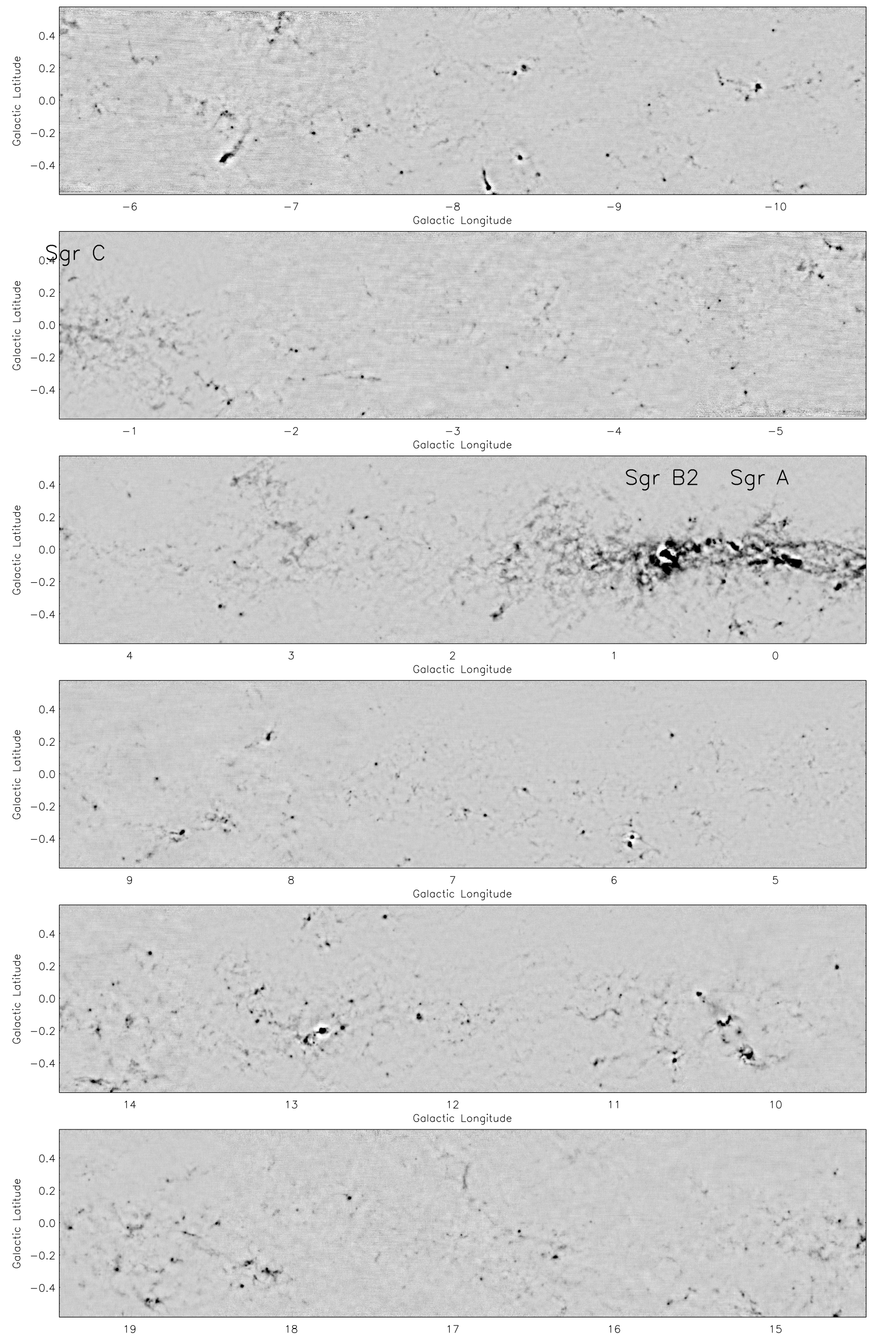

Figure 1. BGPS 1.1 mm continuum map of $-10.5° < l < 19.5°$. The contrast is maximized to highlight the faint sources and extended emission; the light regions around the bright sources are artifacts arising from background subtraction in the vicinity of bright sources. The effective beam size is 33″ FWHM.

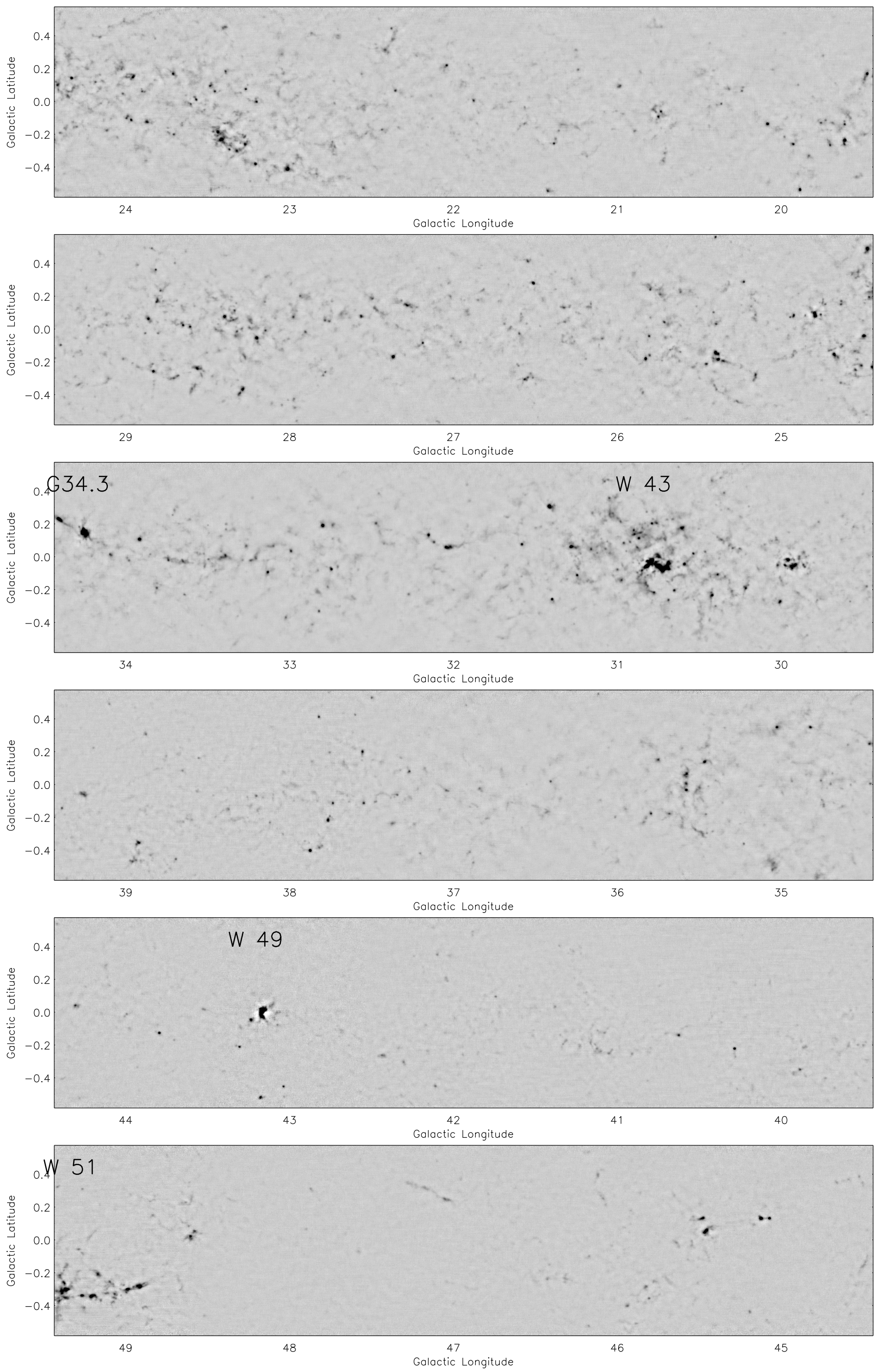

Figure 2. BGPS 1.1 mm continuum map of $19.5° < l < 49.5°$.

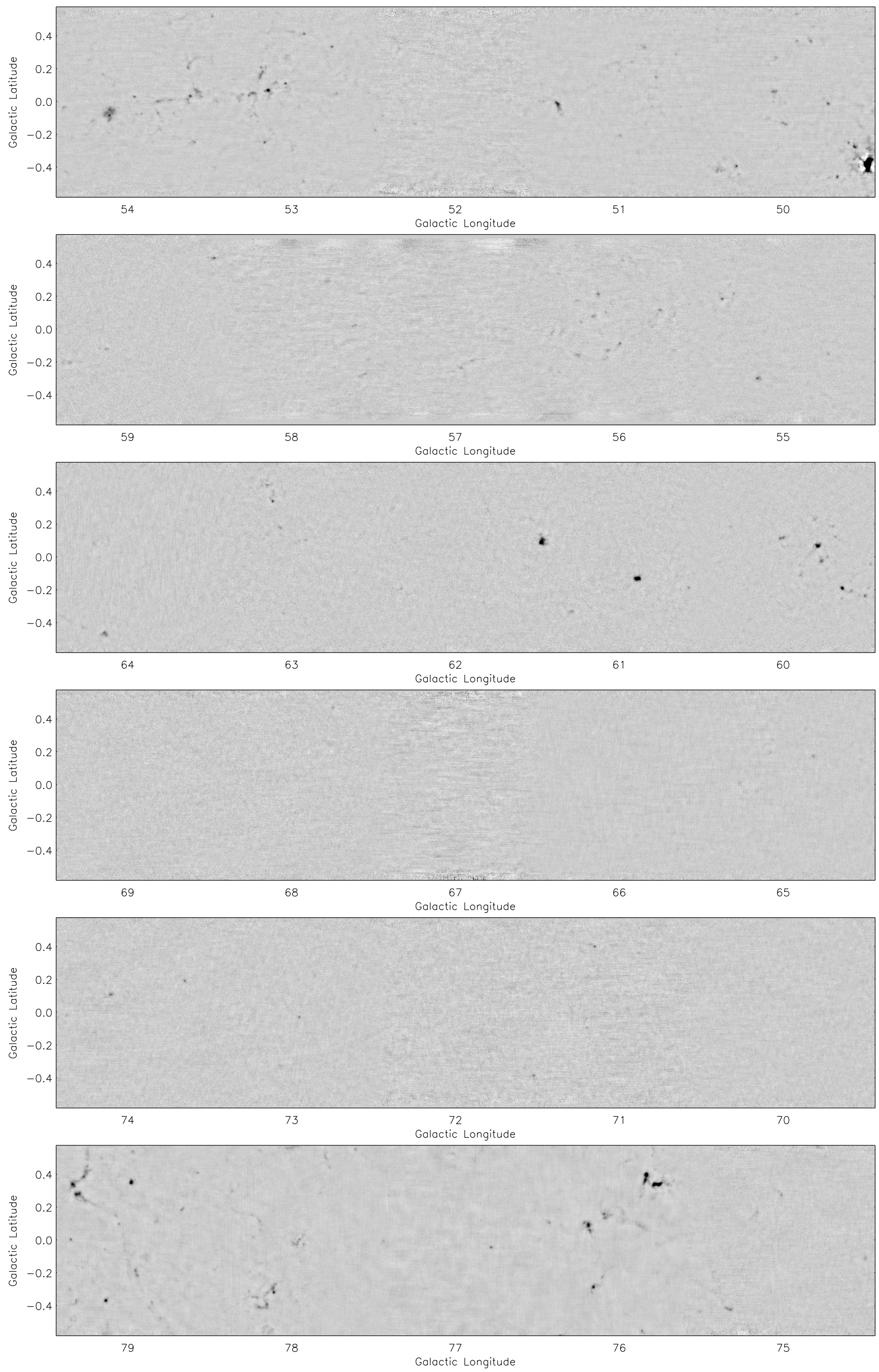

Figure 3. BGPS 1.1 mm continuum map of $49.5^\circ < l < 79.5^\circ$.

Figure 4. BGPS 1.1 mm continuum map of $79.5° < l < 89.5°$, expanded in b in the Cygnus X region to include the DR21 region.

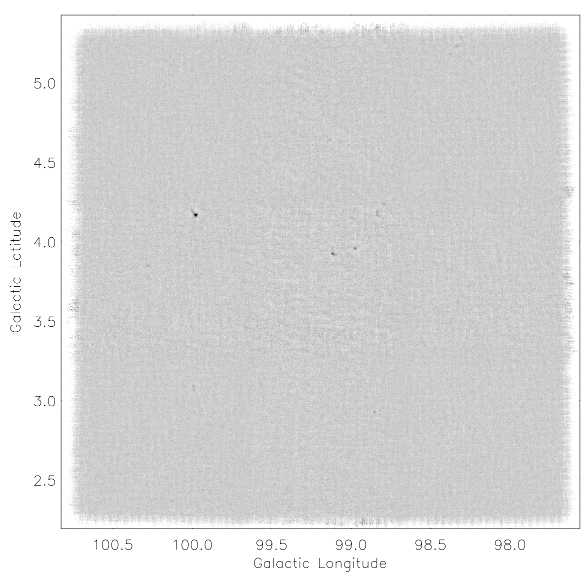

Figure 5. BGPS 1.1 mm continuum map (out of the Galactic plane) in the vicitinity of IC1396.

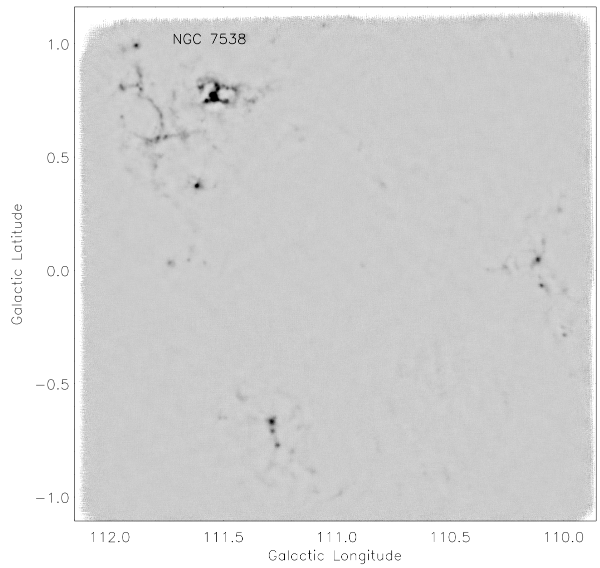

Figure 6. BGPS 1.1 mm continuum map of $110° < l < 112°$, expanded in b, in the Perseus spiral arm.

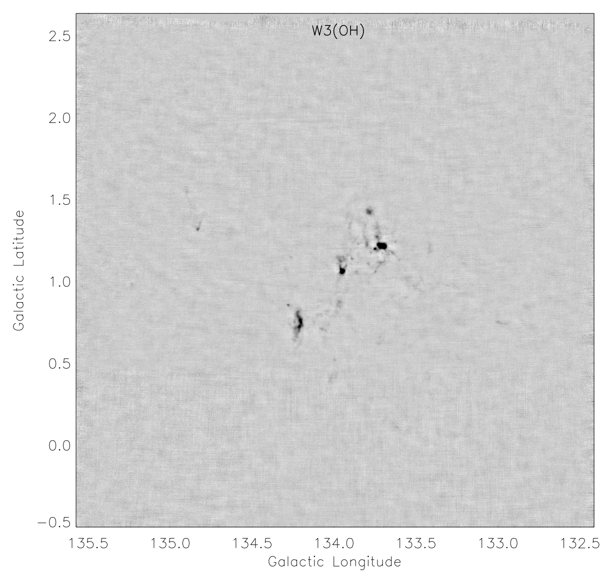

Figure 7. Expanded BGPS 1.1 mm continuum map coverage in the vicinity of W3.

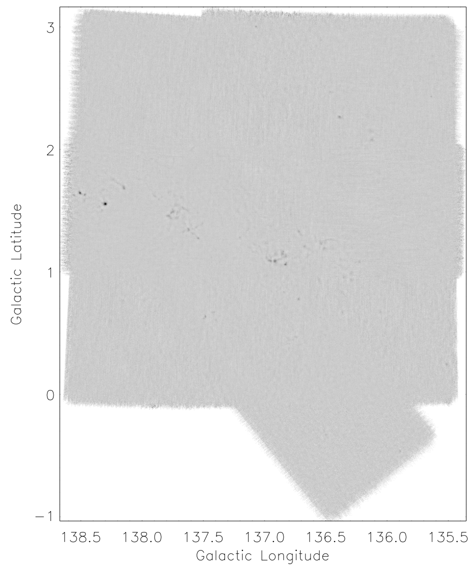

Figure 8. Expanded BGPS 1.1 mm continuum map coverage in the vicinity of W4 and W5.

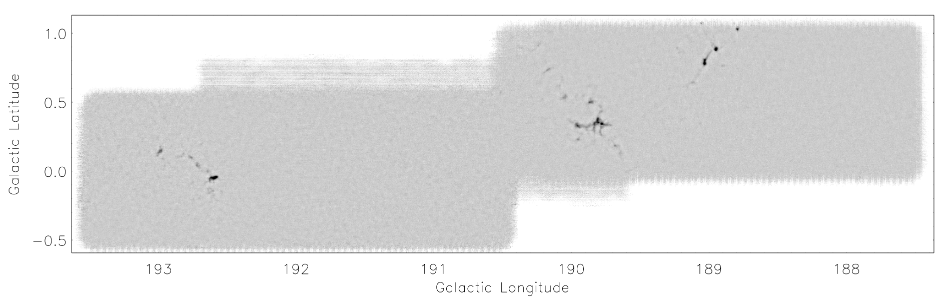

Figure 9. BGPS 1.1 mm continuum map of $187.5° < l < 193.5°$, in the Gem OB1 region.

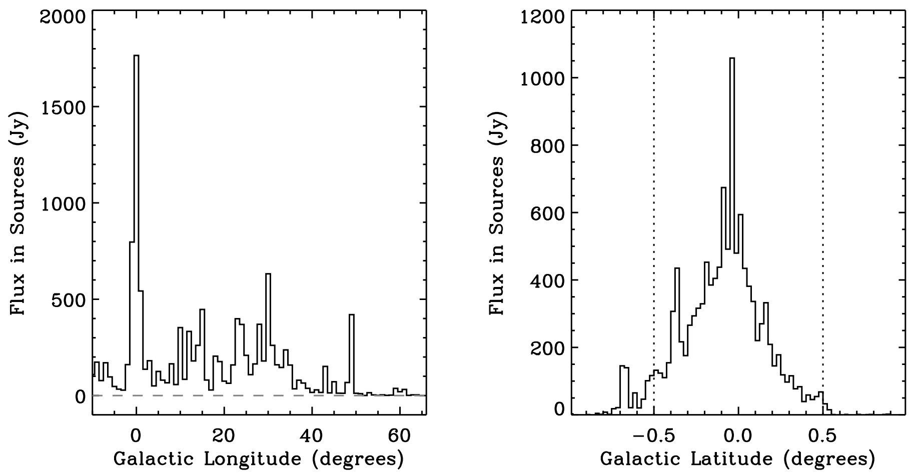

Figure 10. Distribution of total flux density in BGPS catalog sources as a function of Galactic longitude and latitude for the subset of the survey in the range $-10° < l < 66°$.

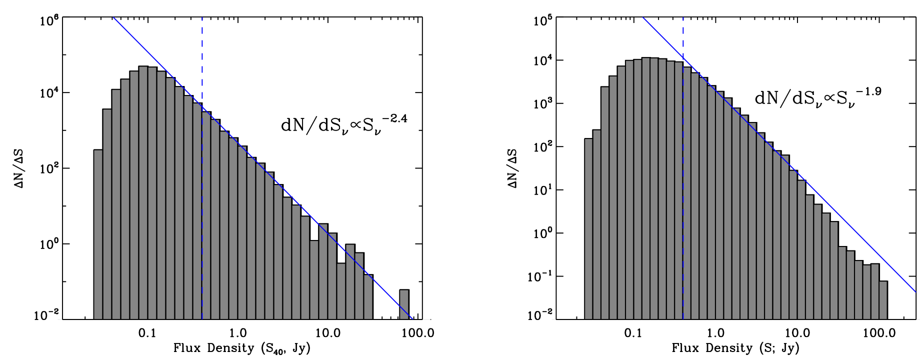

Figure 11. *Left*: Histogram of 1.1 mm flux densities in 40″ apertures of BGPS objects with a power law shown for comparison above the peak. *Right*: Distribution for the total flux density associated with each object.

4 Summary

The BGPS has been completed. The data have been publicly released and are managed within an IPAC archive. Over 8,000 sources of 1.1 mm continuum emission have been detected within the 170 square-degree area of the survey and a follow-up spectroscopy campaign is underway to estimate the distances to the sources using the Galactic rotation curve and to characterize their physical conditions.

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