GODDARD GRANT
IN-89-CR
62494
P. 23

NASA Grant No: NAG 5-1424

Title: Windows in the Milky Way

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Final Report

for Period 10/15/90 – 12/14/91

(NASA-CR-189772) WINDOWS IN THE MILKY WAY Final Report, 15 Oct. 1990 - 14 Dec. 1991 (StarStuff) 23 p CSCL 03A

N92-20146

Unclas

G3/89 0062494

I. Research Aims

During the funded period, our major strategy was two-fold...

(1) To study the IRAS emission levels in the vicinity of Baade's Window and in other optically transparent regions near the Galactic Center.

(2) To study the IRAS emission levels along sightlines in the Milky Way that exhibit very little CO emission.

Through this two-fold strategy, we have endeavored to test whether the optically transparent "windows" near the Galactic center can be identified (as FIR-weak regions) in the IRAS database; and if so, whether the CO-weak regions found elsewhere in the Milky Way represent similarly FIR-weak and thus optically transparent sightlines through the Galaxy. The CO-weak regions have also been targeted in an effort to study the diffuse intercloud dust and its warming by the interstellar radiation field.

Towards the latter part of the funding period, increasing attention was paid to the fine structure of the FIR emission. Through special processing of the IRAS images, we have been able to highlight the fine structure near the Galactic midplane. Its morphology is of special interest, because it provides important clues to the dynamical processes that shape the diffuse interstellar medium — be they 'superbubbles,' 'fountains,' 'chimneys,' 'magnetic flux tubes,' or 'hydro-thermal condensations.'

II. Data Access

Digital tapes containing relevant IRAS images of the Milky Way were created at IPAC by F. Boulanger. These images are mosaics of the IPAC data product BIGMAP. Each one is centered on the Galactic midplane and has a longitudinal extent of 60° and a latitudinal extent of 11°. The pixel size is 3 arcminutes, slightly smaller than the 4 arcminute resolution of the BIGMAP data product. The images have been accessed and analyzed using a variety of image processing systems – initially (10–12/90) at l'Observatoire de Paris, while W. Waller was visiting there, subsequently (1–6/91) at the University of Washington, where Dr. Waller made arrangements to use the U. W. Astronomy Department's computing facilities, and finally (7–12/91) at NASA Goddard Space Flight Center, where Dr. Waller has access to computer services through his NRC Resident Research Associateship there. In October, Dr. Waller had an opportunity to visit IPAC for a week, where he worked with the new Super-Skyflux data product which has yet to be released. His travel and living expenses were paid by IPAC in exchange for consultation services regarding the new data product. Contact with collaborators in France and Holland (recently moved to Germany) has been maintained both personally and through other channels of communication.

Preliminary examination of the IRAS BIGMAP mosaics revealed that the 60 and 100 micron bands were most sensitive to the diffuse emission of interest. Moreover, the 12 and 25 micron bands were most susceptible to striping artifacts in the low-level diffuse emission, most of which is due to variations in the zodiacal emission that were either under or over-subtracted. Even the Super-Skyflux images are affected by residual bands of zodiacal emission (or its negative). Therefore, we have concentrated on the longest wavelength band as the best tracer of the diffuse interstellar dust, while maintaining a watchful eye toward possible zodiacal contamination. The following results are divided according to the two-fold strategy that has been pursued.

III. In and Around Baade's Window

The FIR emission near the Galactic Center is dominated by a nuclear emission excess on top of a background that is strongly peaked toward the midplane (see Figure 1). In this representation, it is not obvious whether Baade's Window and other optically transparent windows (Baade 1946; Lloyd Evans 1976) are associated with holes in the FIR emission. However, longitudinal profiles of the emission reveal that these regions are 20 to 40 percent lower in surface brightness compared to ambient levels. The FIR depressions are especially evident in maps of the residual emission, as generated by subtraction of the smoothly varying Galactic "background" emission from the original imagery (see Figures 2 and 3).

Other residual depressions in the FIR emission are evident at positive Galactic latitude and negative Galactic longitude. Their potential as hitherto unexplored "windows" is being studied through comparisons with optical-infrared data and inferred extinctions in this area.

While at IPAC, Dr. Waller analyzed the Super-Skyflux images to verify whether the same features are evident. Through improved de-striping and co-adding of the raw images, the Super-Skyflux data product has higher signal-to-noise at the lower surface brightness level, and so should provide cleaner maps of the residual emission. Figure 4 shows the resulting map of normalized negative residuals. Comparison with Figure 3 indicates that the same FIR "holes" are present and at even greater strength! Therefore, these features appear to be real depressions in the FIR emission, whose corresponding extinctions may be significantly lower than in their surroundings.

Investigation of the mean relation between the FIR emission and the visual extinction towards the Galactic bulge was pursued by Dr. Waller, using extinction measurements in the literature. The study which spanned the greatest range of extinctions was by Catchpole *et al.* (1985), who conducted infrared scanning of the bulge and used the resulting stellar colors to estimate the variation of extinction with latitude. Their extinctions could be compared with corresponding synthetic "scans" of the FIR emission. The resulting A_v vs. I(100 μm) relation is shown in Figure 5, where the high-extinction points are from Catchpole *et al.* and the lower-extinction points are from other sources (based on stellar photometry within known "windows." A strong correlation is evident for extinctions exceeding 1 mag which can be fit by

$$logI(100\mu m) = (1.71 \pm 0.04) + (1.47 \pm 0.08) logA_v.$$

Surprisingly, this relation is non-linear, suggesting that greater dust emissivities exist in dustier environments — perhaps because these are closer to the Galactic midplane, where the interstellar radiation field would be more intense. For extinctions of 1 – 2 mag, the 100 μm emissivity is about 70 MJy sr^{-1}/mag. This is roughly 10 times higher than that measured in the high-latitude "cirrus" emission. Such a discrepancy highlights the much stronger interstellar radiation field near the bulge compared to the Solar neighborhood.

Moreover, it serves notice to those who wish to use a galaxy's 100 μm emission as a tracer of star formation: They may incur serious errors in bulge environments or in bulge-dominated galaxies, where the emission has little to do with recent star formation.

Some of these results were discussed in a brief oral presentation by Dr. Waller at the Summer 1991 meeting of the American Astronomical Society (Seattle, May 26–30).

IV. In and Around CO-Weak Regions

In the first Galactic quadrant, as elsewhere beyond the Galactic Center, the FIR emission is dominated by local complexes of giant HII regions and molecular clouds, again on top of a background that is strongly peaked toward the Galactic midplane. Figure 6 shows a 22° × 22° region in the direction of the Aquila Rift system of molecular clouds, estimated to be only 200 pc away (Dame and Thaddeus 1985). Once again, the strong latitudinal gradient in FIR emission makes it difficult to immediately associate FIR-weak regions with CO-weak regions. Nevertheless, longitude profiles and median-filtered images reveal that correspondences do exist (see Figures 6, 7, 8). However, there are many other FIR depressions which are not associated with CO-weak regions. Their significance awaits further study.

Photometry of the FIR emission in each of the 2172 CO-weak sightlines previously identified by Waller *et al.* 1991 and the 172 sightlines identified by Verter *et al.* 1983 has been carried out. We intend to compare the fluxes and colors along these sightlines with their counterparts at neighboring longitude and/or opposite latitude. Preliminary analysis indicates that the CO-weak sightlines exhibit weaker FIR emission than their opposite-latitude counterparts 83 percent of the time. We hope to supplement these comparisons with similarly resolved HI data in an effort to evaluate the content, radiative environment, and emissive properties of the diffuse intercloud medium. One compatible HI study has been conducted by Lockman and Ganzel (1983) where the resolution was 20 arcminutes (see also Bregman and Ashe 1991). Higher resolution mapping (FWHM $\approx$ 4') has been conducted with the Arecibo dish for selected portions of the Galactic plane (T. Bania, private communication), but these results are not yet available. We will also compare the

CO/FIR data with corresponding maps of visual extinction. The photometric study by Forbes (1985) for the longitude range 30° – 70° is perhaps the most compatible with our data. Less quantitative but more thorough mappings of obscuration (e.g. Lynds 1965) will also be accessed.

V. Far Infrared Fine Structure

As described above, our image processing revealed peaks and valleys in the residual FIR emission that span several degrees. The processing also revealed diaphanous fine structure in the FIR emission with size scales as small as the 4' × 4' resolution of the images. To confirm this fine structure, Dr. Waller performed the same image processing on a mosaic of Super-Skyflux images while he was at IPAC. The resulting image of normalized residual emission is shown in Figure 9. This image reveals that the FIR "cirrus" emission extends all the way to the Galactic midplane. The bright source evident at high latitude is the Rho Ophiucus cloud complex, thought to be a few hundred parsecs away. The fact that its extensions blend into the tangle of FIR fine structure suggests that most of this structure is from dust within a few hundred parsecs. At negative latitudes (not shown here) the R Corona Austrina cloud is evident as a bright source overlain upon the FIR fine structure, as if it is closer to us than the surrounding structure. We hope to use these morphological clues to better constrain the whereabouts of the FIR fine structure (aka cirrus).

Although we had expected to find morphological evidence for supernova-driven "supershells" and "worms" (cf. Bregman and Ashe 1991; Koo *et al.* 1991), the far-infrared fine structure appears more complex (e.g. less coherent) as viewed in projection. This may be due to its relative proximity, thus biasing our view towards processes that sculpt the interstellar medium on small size scales. We look forward to further investigating the FIR fine structure near the Galactic midplane — determining its spatial power spectra at different longitudes and comparing them with similarly determined spectra at higher latitude. We also anticipate comparing this structure with visible images of the dark clouds as well as maps of the HI, CO, and Hα emission. Visual inspection of optical photographs have already revealed strong correspondences between dark lanes of dust and the FIR fine structure.

VI. Research Prospects

During the funded research period, we have explored the Galactic FIR emission as it relates to visual extinctions, CO emission, the interstellar radiation field, and the structure of the diffuse interstellar medium. Some of our results were more ambiguous than expected (e.g. the relation between CO and FIR "holes"), while others were surprisingly evident (e.g. the FIR fine structure near the Galactic midplane). We intend to continue these investigations, using the available data for the next year or so. We may then decide to work more intensively with the IRAS Super-Skyflux data product after its official release, funding the research through another ADP grant perhaps. We may also decide to get more serious about comparing the FIR emission with the HI emission (making additional Arecibo observations if necessary), the Hα emission (using a wide-field Lyot camera being developed at NASA/GSFC), and the CO emission (especially towards the Galactic bulge, using the ESO SIST telescope).

VII. Publications Related to the NASA/ADP Grant

Waller, W. H. 1991, "Far Infrared Emission Levels in and around Baade's Window," *Bull. A. A. S.*, **23**, 960.

Waller, W. H. and Tacconi-Garman, L. E. 1992, "Walls and Windows in the Molecular Milky Way," *Ap. J. Suppl.*, in press.

Waller, W. H., Boulanger, F., Okumura, K, and Tacconi-Garman, L. E. 1992, "Fine Structure in the Far Infrared Milky Way," in preparation.

Waller, W. H., Boulanger, F., and Tacconi-Garman, L. E. 1992, "Far-Infrared Emission and Visual Extinction Towards the Galactic Bulge: Evidence for New Windows?," in

preparation.

References

Azzopardi, M., Lequeux, J., Rebeirot, E., and Westerlund, B. E. 1992, *Astr. Ap. Suppl.*, in press.

Baade, W. 1946, *Pub. A. S. P.*, **58**, 249.

Bregman, J. N. and Ashe, G. A. 1991, in *The Interstellar Disk-Halo Connection in Galaxies, IAU Symposium #144*, p. 387.

Catchpole, R. M., Whitelock, P. A., Glass, I. S. 1985, in *The Milky Way Galaxy, IAU Symposium #106*, (Dordrecht: Reidel) p. 127.

Dame, T. M. and Thaddeus, P. 1985, *Ap. J.*, **297**, 751.

Forbes, D. 1985, *A. J.*, **90**, 301.

Koo, B. C., Heiles, C., and Reach, W. T. 1991, in *The Interstellar Disk-Halo Connection in Galaxies, IAU Symposium #144*, p. 165.

Lloyd Evans, T. 1976, *M. N. R. A. S.*, **174**, 169.

Lockman, F. J. and Ganzel, B. L. 1983, *Ap. J.*, **268**, 117.

Lynds, B. T. 1966, *Ap. J. Suppl.* **12**, 163.

Oort, J. H. and Plaut, L. 1975, *Astr. Ap.*, **63**, 7.

van den Bergh, S. 1972, *Pub. A. S. P.*, **84**, 306.

van den Bergh, S. and Herbst, E. 1974, *A. J.*, **79**, 603.

Verter, F., Knapp, G. R., Stark, A. A., and Wilson, R. W. 1983, *Ap. J. Suppl.*, **52**, 289.

Waller, W. H., and Tacconi-Garman, L. E. 1992, *Ap. J. Suppl.*, in press.

Westerlund, B. E., Lequeux, J., Azzopardi, M., and Rebeirot, E. 1992, *Astr. Ap.*, in press.

Figure Captions

1. Contour diagram of the 100 micron surface brightness in the direction of the Galactic center. The mapping is from the BIGMAP data product. The field of view is 22° × 22°. The emission is contoured logarithmically in intervals of 0.25 dex beginning at $10^{1.25}$ MJy/Sr. Well known optically transparent regions (Baade 1946; Lloyd Evans 1976) are labeled... Baade's Window (BW), Sagittarius I (Sgr I), and Sagittarius II (Sgr II).

2. Contour diagram of the 100 μm emission deficits or "holes" near the Galactic center after median filtering the original 100 μm image. Same field of view as before. Optically transparent regions are indicated. The filtration process involved median smoothing the original 60° × 22° image in the longitudinal direction (using a 10.0° × 0.05° window) and then subtracting this smoothed image from the original image. This removes the strong latitudinal gradient in the emission. Only the negative emission residuals are contoured here, in intervals of –100 MJy/Sr beginning at –100 MJy/Sr. The greater deficits near the Galactic midplane are consequences of there being higher levels of emission at low latitude in the original image and hence larger amplitude fluctuations about these levels.

3. Contour diagram of the 100 μm negative emission residuals near the Galactic center after dividing the median filtered image (see Figure 2) by the median smoothed image. This normalizes the emission deficits as fractions of the ambient emission. Only the negative normalized residuals are plotted here, in intervals of –0.1 beginning at –0.1. Same field of view as before. Optically transparent regions are indicated.

4. Same as Figure 3, except using the Super-Skyflux data product instead of the BIGMAP data product. The Super-Skyflux data product is claimed to be less degraded by striping and other artifacts and to have a higher signal-to-noise overall. Similar features of negative residuals are evident — with even greater strengths — thus corroborating the discovery of "holes" in the FIR emission.

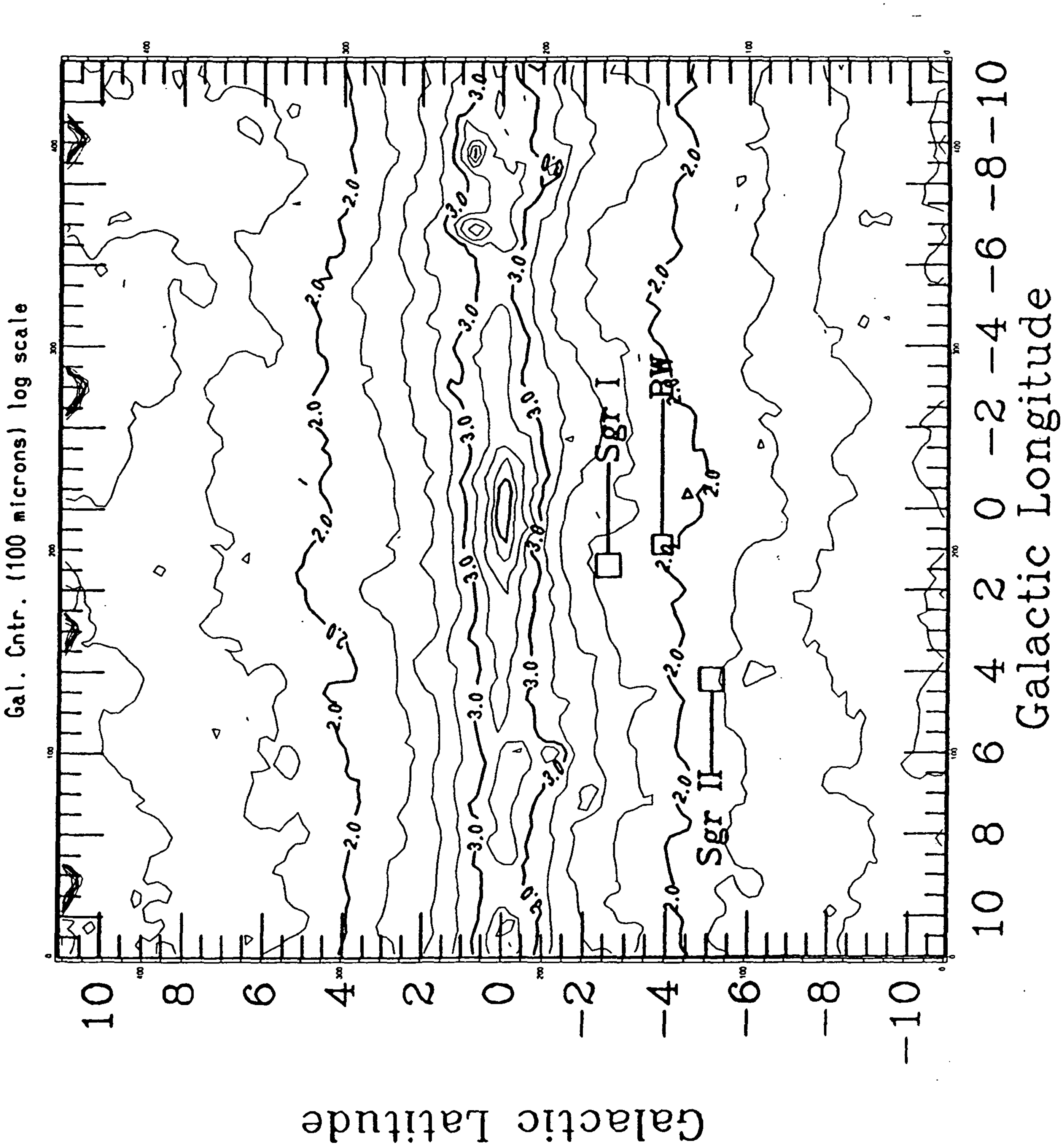
5. Relation between the visual extinction and the 100 micron surface brightness towards the Galactic bulge. The extinctions are obtained from a number of sources in the literature: The squares are from the infrared scanning results of Catchpole *et al.* 1985. The circles are from the infrared photometry of Carbon stars by Azzopardi *et al.* 1991 and subsequent analysis by Westerlund *et al.* 1991. The X marks are from the BVI stellar photometry of Terndrup 1988. The stars are from optical stellar photometry in the well-known "windows" by Baade 1946, van den Bergh 1972, van den Bergh and Herbst 1974, Oort and Plaut 1975, and Lloyd Evans 1976.

6. Contour diagram of the 100 μm surface brightness in the direction of the Aquila Rift system of molecular clouds (Dame and Thaddeus 1985). The mapping is from the BIGMAP data product. The field of view is 22° × 22°. The emission is contoured logarithmically in increments of 0.25 dex beginning at $10^{1.5}$ MJy/Sr. CO-weak regions identified by Waller *et al.* 1991 are indicated by crosses; CO-weak regions identified by Verter *et al.* 1983 are indicated by asterisks.

7. Contour diagram of the 100 μm emission deficits or "holes" in the direction of the Aquila Rift system of molecular clouds after median filtering the original 100 μm image. Same field of view as before. Only the negative emission redsiduals are contoured, in intervals of –100 MJy/Sr beginning at –100 MJy/Sr. The greater deficits near the Galactic midplane are consequences of there being higher levels of emission at low latitude in the original image and hance larger amplitude fluctuations about these levels. CO-weak regions are indicated by crosses (Waller *et al.* 1991) and asterisks (Verter *et al.* 1983).

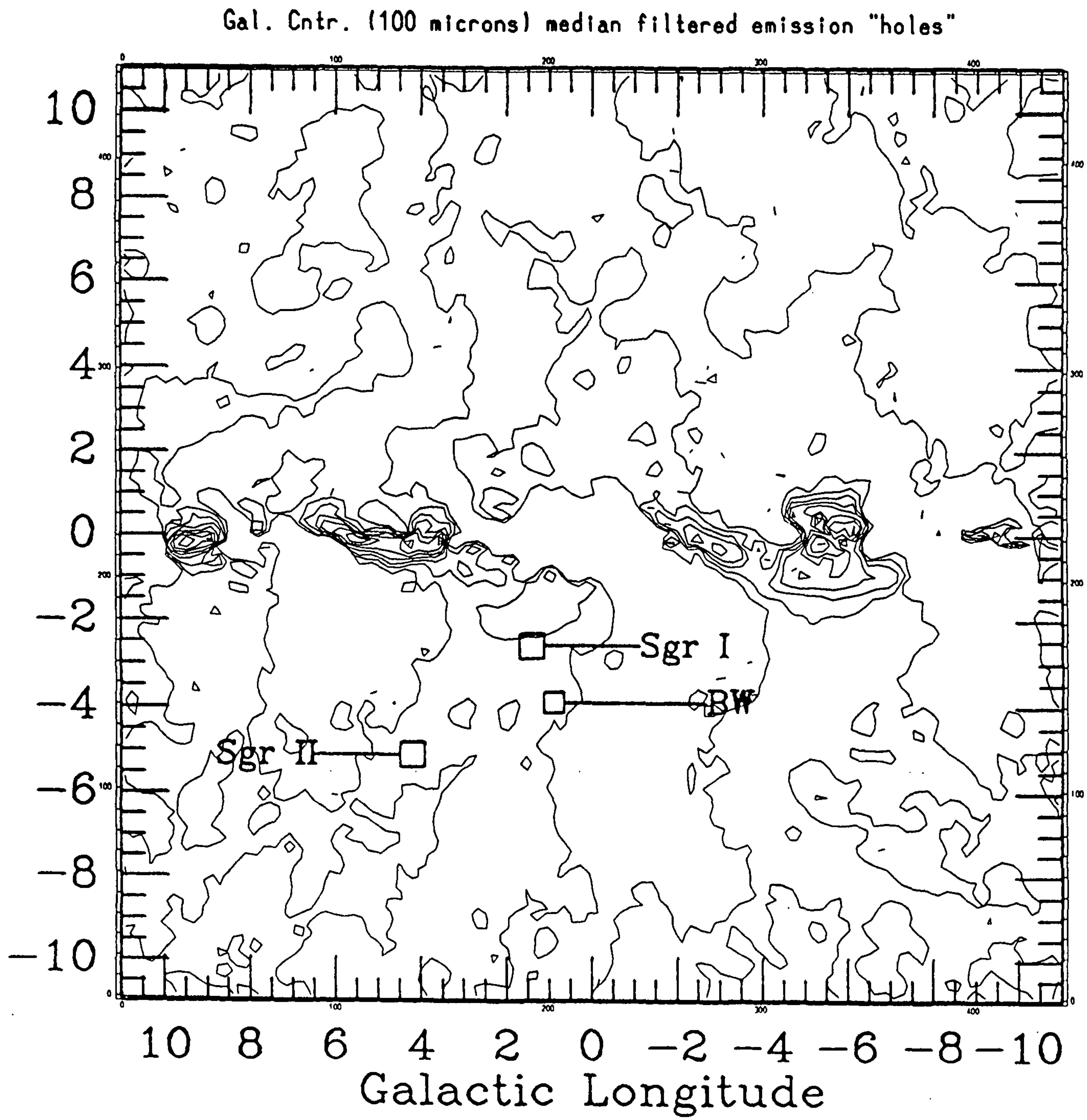
8. Contour diagram of the 100 μm negative emission residuals in the Aquila Rift region after dividing the median filtered image (see Figure 7) by the median smoothed image. This normalizes the emission deficits as fractions of the ambient emission. Only the negative normalized residuals are plotted, in intervals of –0.1 beginning at –0.1. Same field of view as before. CO-weak regions are indicated by crosses (Waller *et al.* 1991) and asterisks (Verter *et al.* 1983).

9. Image of the normalized emission residuals at 100 microns in the direction of the Galactic bulge. The image is a mosaic of Super-Skyflux frames, centered in longitude about the Galactic center and spanning approximately 50° in both longitude and latitude. This image shows the fine structure in the FIR emission. It reveals that the FIR "cirrus" emission extends all the way to the Galactic midplane. The bright source at high latitude is the Rho Ophiucus complex. Its extensions blend into the tangle of FIR fine structure, thus indicating that most of the fine structure is from sources within a few hundred parsecs of the Sun.



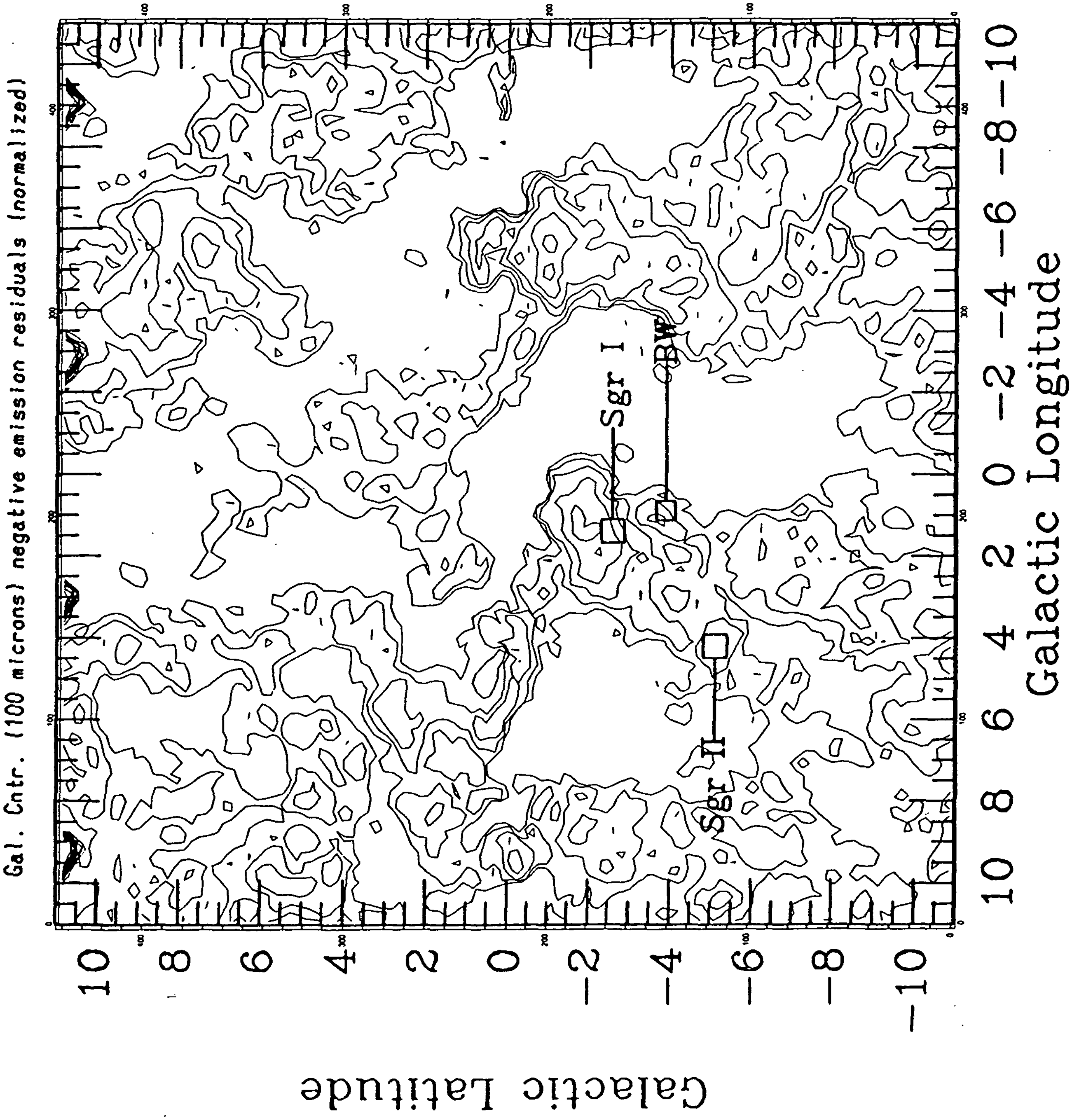
Gal. Cntr. (100 microns) log scale
Galactic Longitude
Galactic Latitude
Sgr I
Sgr II
BW
10 8 6 4 2 0 -2 -4 -6 -8 -10
10 8 6 4 2 0 -2 -4 -6 -8 -10
2.0
3.0

Figure 1



Gal. Cntr. (100 microns) median filtered emission "holes"
Galactic Latitude
Galactic Longitude
10
8
6
4
2
0
−2
−4
−6
−8
−10
Sgr I
BW
Sgr II

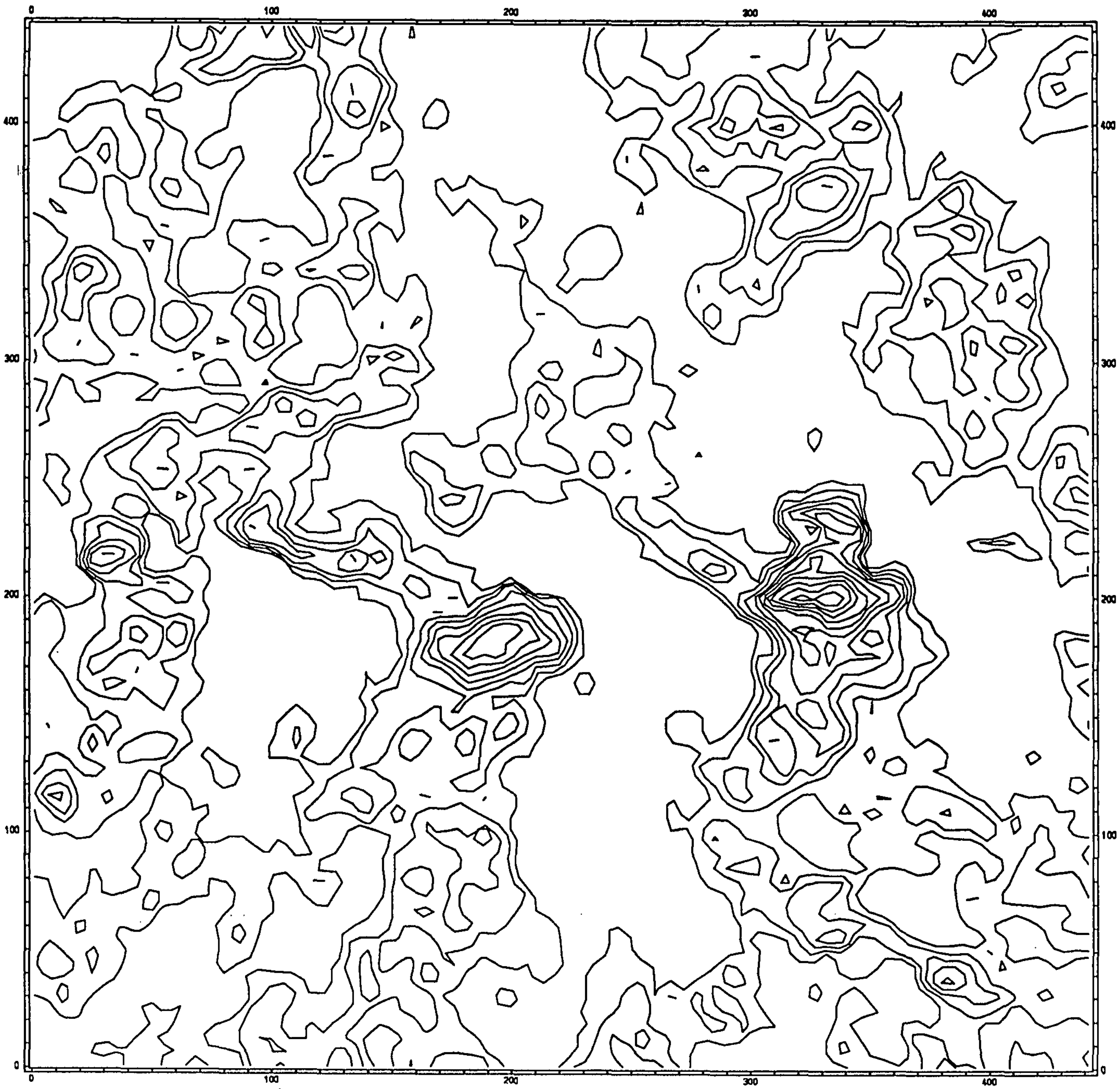
Figure 2



Gal. Cntr. (100 microns) negative emission residuals (normalized)
Galactic Longitude
Galactic Latitude
10 8 6 4 2 0 −2 −4 −6 −8 −10
10 8 6 4 2 0 −2 −4 −6 −8 −10
Sgr I
BW
Sgr II

Figure 3

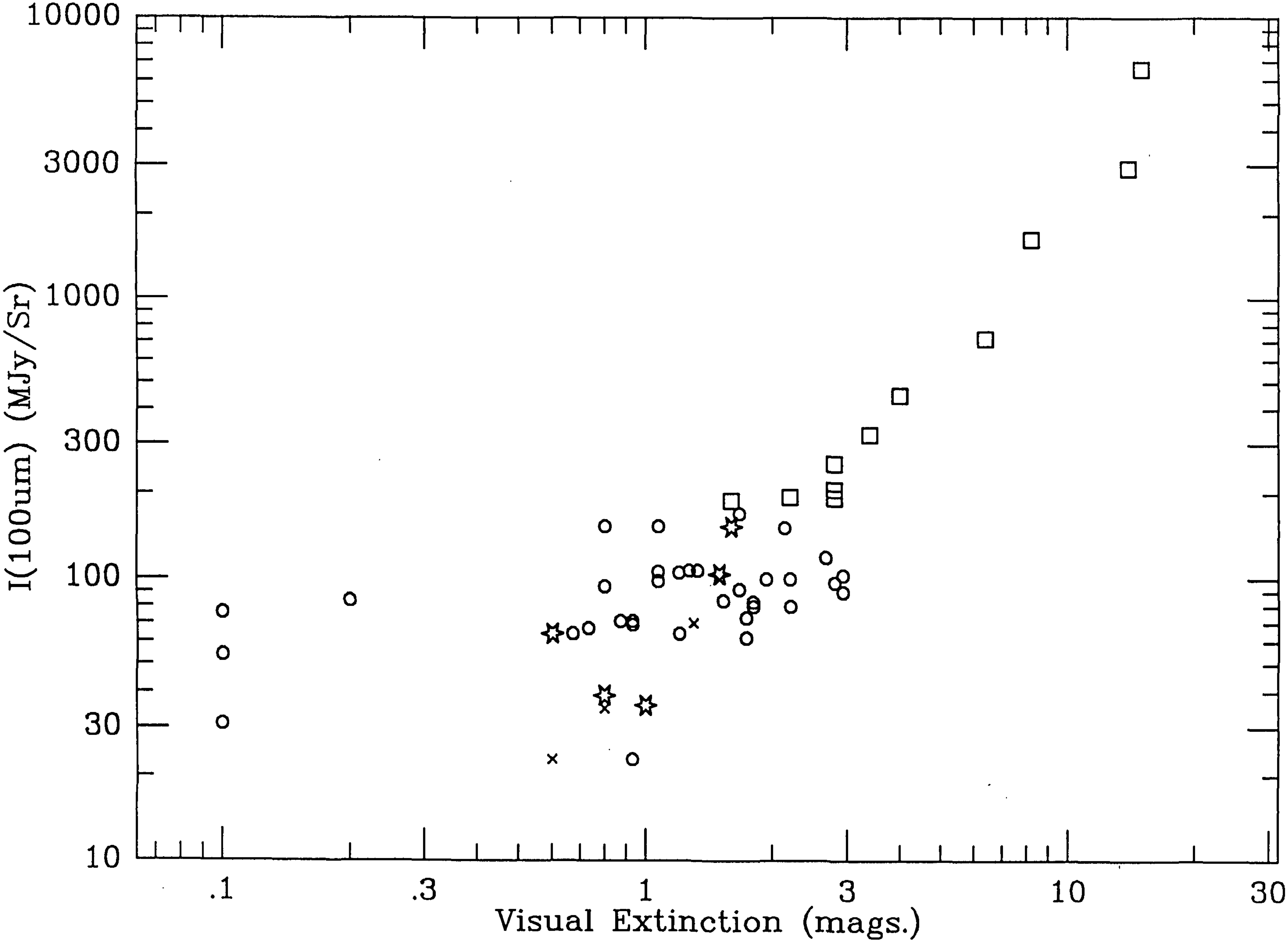
Normalized Negative Residuals (100um)



contoured from 0. to 1., interval = 0.1

NOAO/IRAF V2.9.1EXPORT ipacc27@nimoy.ipac.caltech.edu Mon 19:12:35 14-Oct-91

Figure 4



10000
3000
1000
300
100
30
10
I(100um) (MJy/Sr)
.1
.3
1
3
10
30
Visual Extinction (mags.)

Figure 5

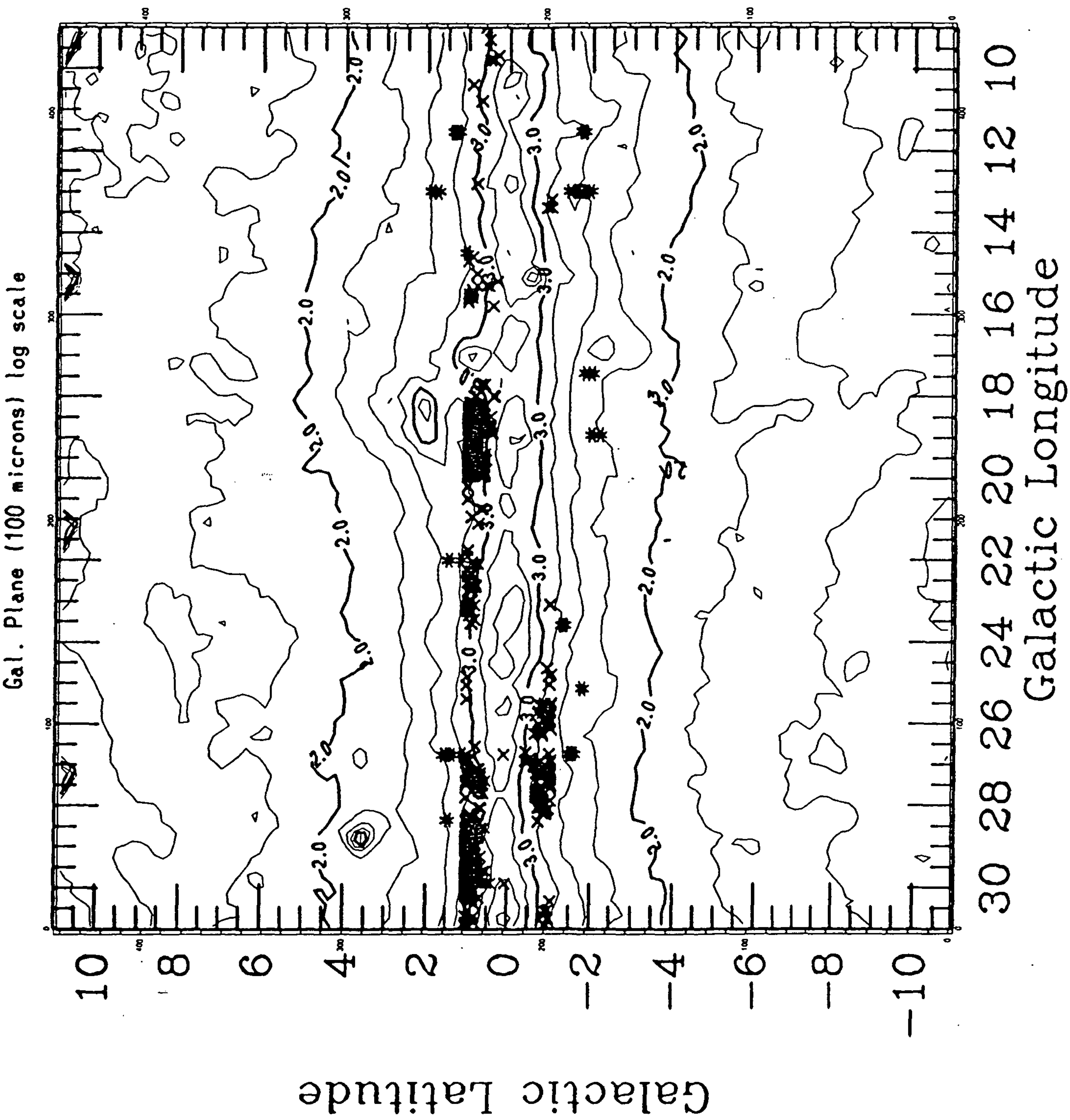

Gal. Plane (100 microns) log scale
Galactic Longitude
Galactic Latitude
30 28 26 24 22 20 18 16 14 12 10
10 8 6 4 2 0 −2 −4 −6 −8 −10
2.0
3.0

Figure 6

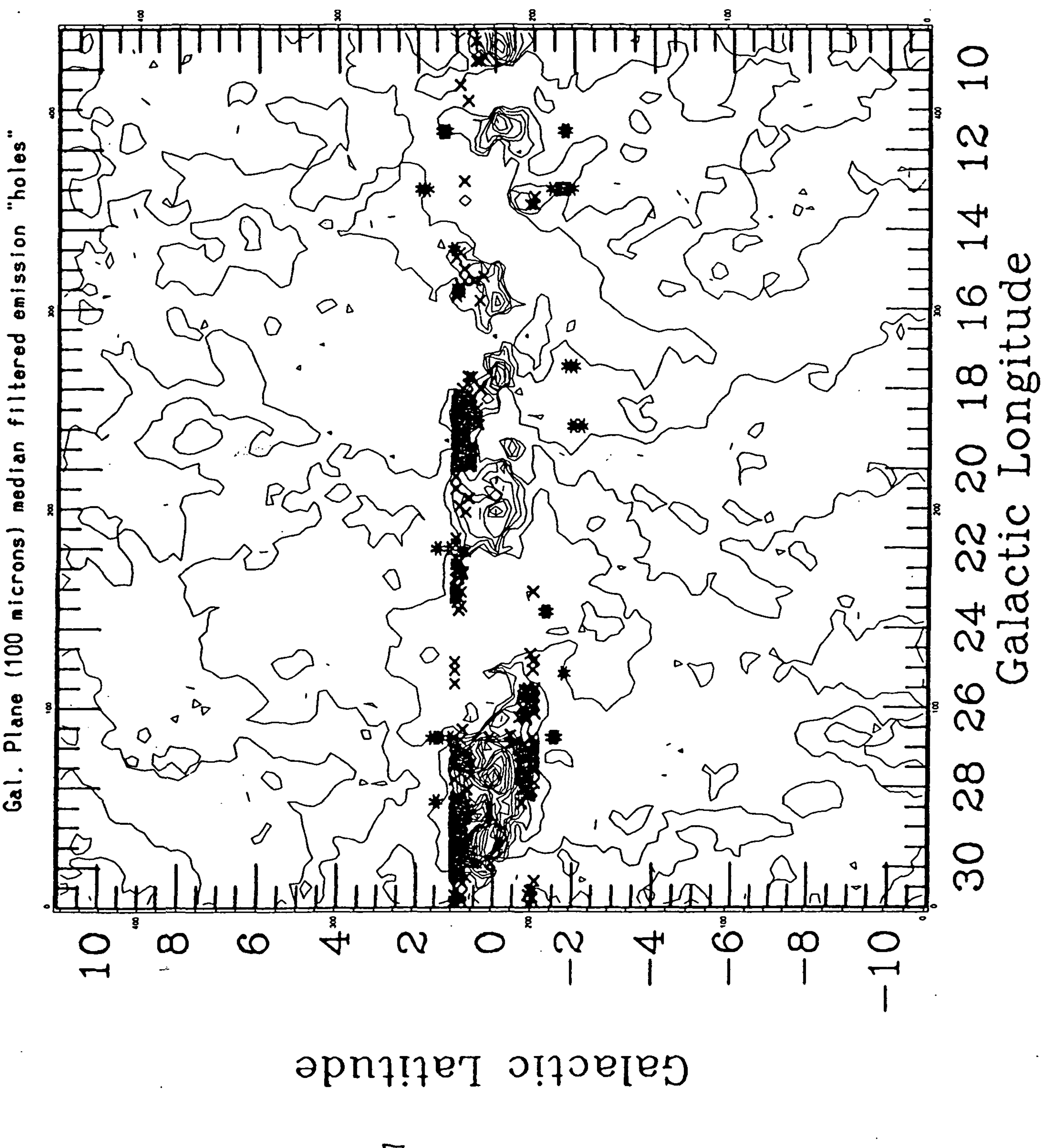

Gal. Plane (100 microns) median filtered emission "holes"
Galactic Longitude
Galactic Latitude
30 28 26 24 22 20 18 16 14 12 10
10 8 6 4 2 0 -2 -4 -6 -8 -10

Figure 7

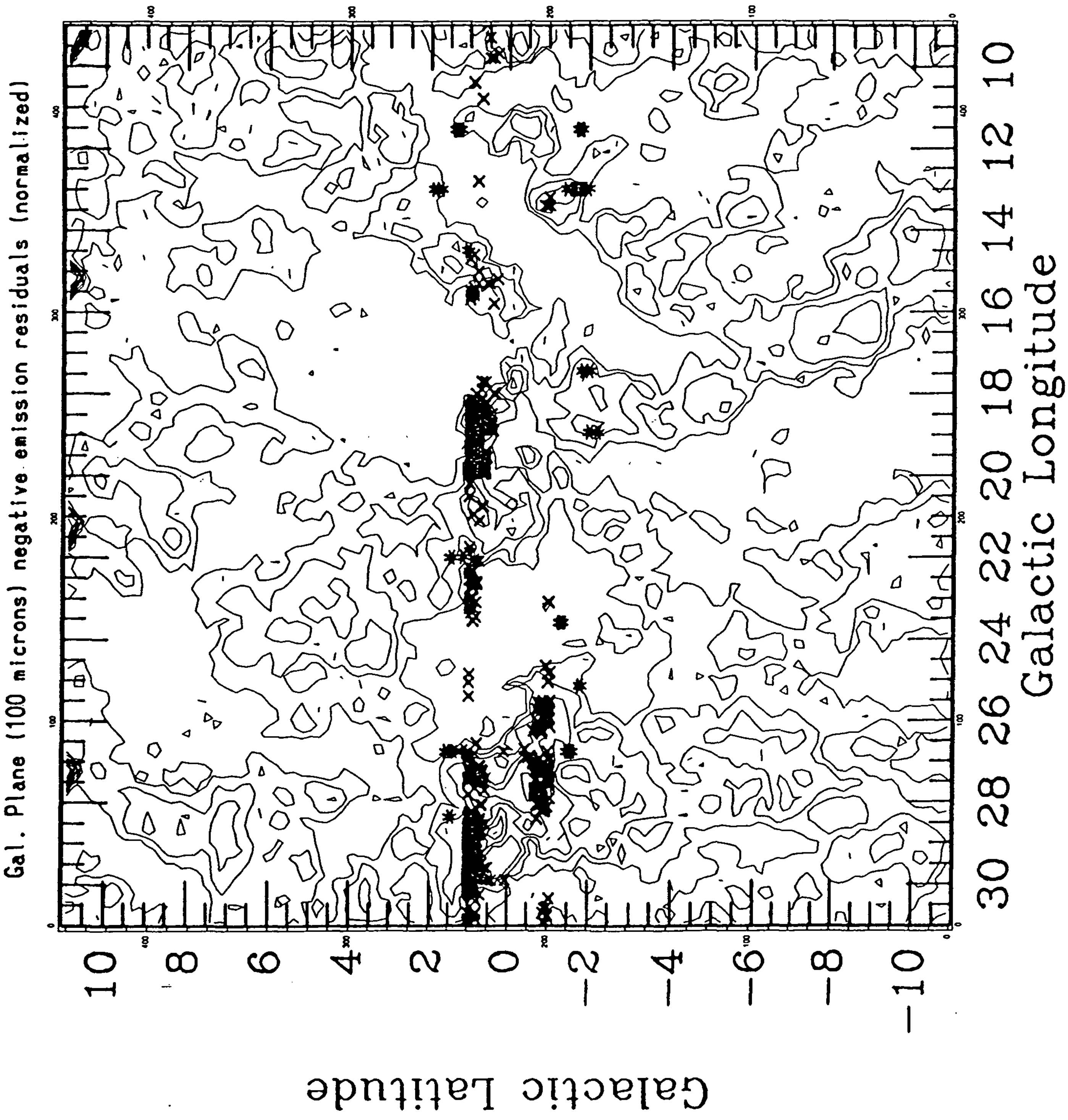

Gal. Plane (100 microns) negative emission residuals (normalized)
30 28 26 24 22 20 18 16 14 12 10
Galactic Longitude
10 8 6 4 2 0 −2 −4 −6 −8 −10
Galactic Latitude

Figure 8

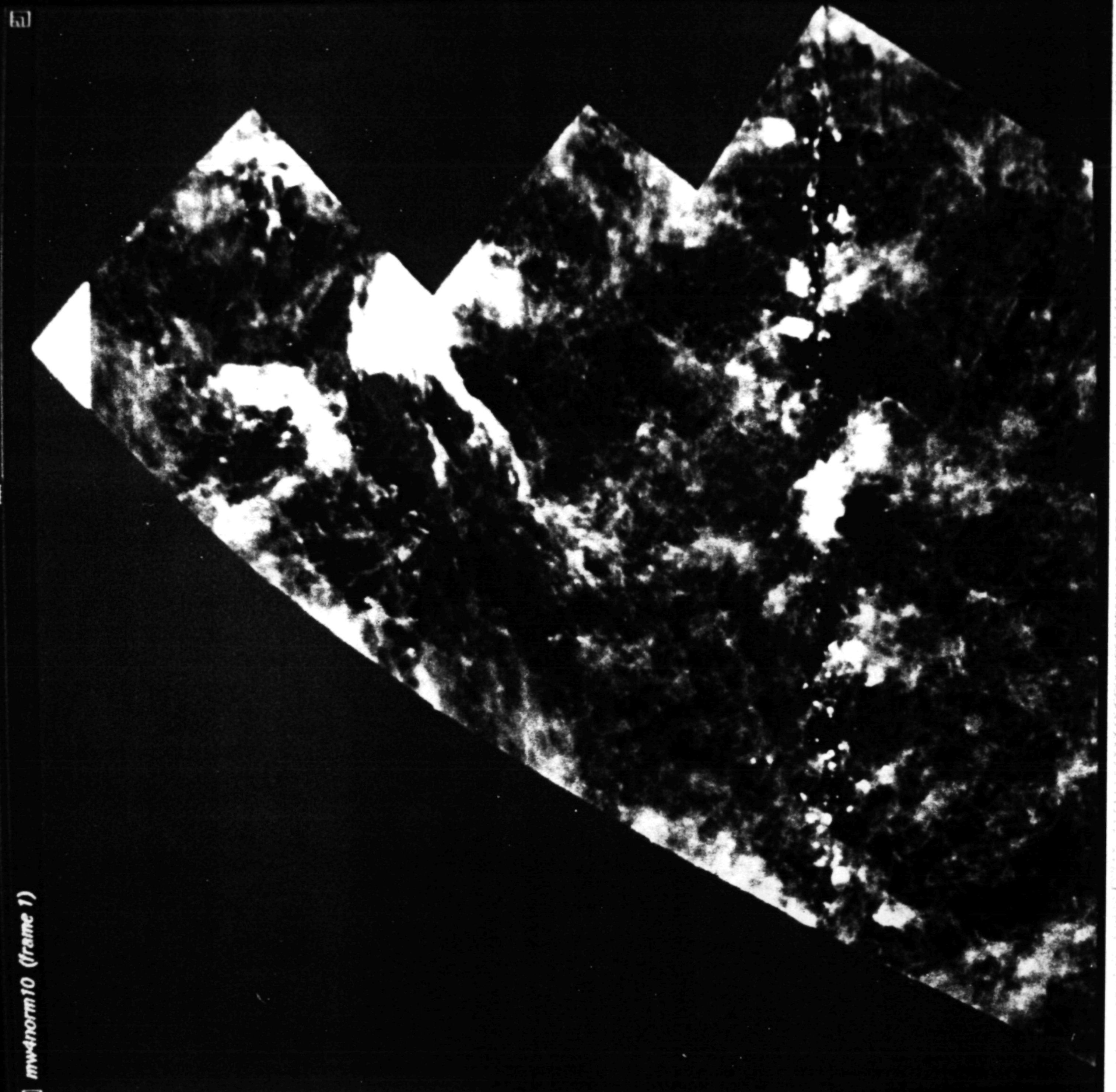


Figure 9

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'ar – Infrared Emission Levels
ı and around Baade's Window

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ınalysis of IRAS emission levels near the Galactic Center have revealed ignificant depressions in FIR intensity in Baade's window (ℓ,b = 0.9, 3.9) and in other well-known optically transparent regions at negative ıtitude. The drop in emission compared to ambient levels amounts to 0-40 percent at 100 microns. The FIR depressions are especially evlent in maps of the residual emission, as generated by subtraction of he smoothly varying Galactic emission from the original imagery. Other esidual depressions in the FIR emission are evident at positive Galacic latitude and negative Galactic longitude. Their potential as hitherto ınexplored "windows" is discussed.

'his research received support via NASA/ADP grant # NAG 5-1424.

published in B.A.A.S.

Abstract Submitted for the 178th Meeting of the AAS, Seattle, Washington

Date Submitted March 19, 1991 Form Version 1/91

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