The disruption of nearby galaxies by the Milky Way

M. E. Putman[1], B. K. Gibson[1], L. Staveley-Smith[2], G. Banks[3], D. G. Barnes[4], R. Bhatal[5], M. J. Disney[3], R. D. Ekers[2], K. C. Freeman[1], R. F. Haynes[2], P. Henning[6], H. Jerjen[1], V. Kilborn[4], B. Koribalski[2], P. Knezek[7], D. F. Malin[8], J. R. Mould[1], T. Oosterloo[9], R. M. Price[2], S. D. Ryder[10], E. M. Sadler[11], I. Stewart[2], F. Stootman[5], R. A. Vaile[5†], R. L. Webster[4], A. E. Wright[2]

[1]Mount Stromlo & Siding Spring Observatories, Australian National University, Weston Creek P.O., Weston, ACT 2611, Australia

[2]Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 2121, Australia

[3]University of Wales, Cardiff, Department of Physics & Astronomy, P.O. Box 913, Cardiff CF2 3YB, Wales, United Kingdom

[4]University of Melbourne, School of Physics, Parkville, Victoria 3052, Australia

[5]University of Western Sydney Macarthur, Department of Physics, P.O. Box 555, Campbelltown, NSW 2560, Australia

[6]University of New Mexico, Department of Physics & Astronomy, 800 Yale Blvd. NE, Albuquerque, NM 87131, USA

[7]The Johns Hopkins University, Department of Physics & Astronomy, 34$^{\text{th}}$ & North Charles Streets, Baltimore, MD 21218, USA

[8]Anglo-Australian Observatory, P.O. Box 296, Epping, NSW 2121, Australia

[9]Istituto di Fisica Cosmica, via Bassini 15, I-20133, Milano, Italy

[10]Joint Astronomy Center, 660 North Aohoku Place, Hilo, HI 96720, USA

[11]University of Sydney, Astrophysics Department, School of Physics, A28, Sydney, NSW 2006, Australia

[†]deceased

Interactions between galaxies are common and are an important factor in determining their physical properties such as position along the Hubble sequence and star-formation rate[1]. There are many possible galaxy interaction mechanisms, including merging, ram-pressure stripping, gas compression, gravitational interaction and cluster tides[2]. The relative importance of these mechanisms is often not clear, as their strength depends on poorly known parameters such as the density, extent and nature of the massive dark halos that surround galaxies[3]. A nearby example of a galaxy interaction where the mechanism is controversial is that between our own Galaxy and two of its neighbours – the Large and Small Magellanic Clouds. Here we present the first results of a new H I survey which provides a spectacular view of this interaction. In addition to the previously known Magellanic Stream[4], which trails 100° behind the Clouds, the new data reveal a counter-stream which lies in the opposite direction and leads the motion of the Clouds. This result supports the gravitational model in which leading and trailing streams are tidally torn from the body of the Magellanic Clouds.

The Magellanic Stream, discovered 25 yrs ago[4], is a narrow ($\sim 10^\circ$ wide) tail of neutral hydrogen, which trails the Magellanic Clouds along a circle around the Milky Way. The past two decades have seen the number of viable mechanisms for its formation reduced to two - *ram-pressure stripping* of material from the Magellanic System during its passage through the Galactic halo or extended ionised disk[5–8], and *tidal interaction* of the Magellanic Clouds with the Milky Way[9–14]. Although tidal models have been successful in explaining many characteristics of the Stream, they have suffered from two major drawbacks: (a) the absence of stars in the Stream[15] (stars are also affected by tidal forces), and (b) the lack of evidence for a leading stream, or arm, which is a natural consequence of tidal interaction[9–12]. Discrete neutral hydrogen clouds on the leading side have been known for some time, but have generally been regarded as a separate group of high velocity clouds[5,6].

The H I Parkes All-Sky Survey (HIPASS)[16] is a new survey for H I in the southern sky ($\delta \leq 0^\circ$) over the velocity range -1,200 to 12,700 km s^{-1}. It therefore spans the Milky Way, the Magellanic Clouds and the more distant Universe. The 64-m Parkes telescope, with a focal-plane array of 13 beams, set in a hexagonal grid, is being used to survey the sky in 8° zones of declination, with approximate Nyquist sampling. The spectrometer has 1024 channels for each polarisation and beam, with a velocity spacing of 13.2 km s^{-1} and a spectral resolution, after Hanning smoothing, of 26.4 km s^{-1}. Whilst not ideal for resolving fine spectral structure, accurate column densities and velocity fields are obtained. The HIPASS survey will scan the entire southern sky five times for full sensitivity. The data presented here come from the first scan only and cover the sky south of declination -62°. The rms brightness temperature sensitivity is approximately 20 mK, corresponding to a column density sensitivity of 10^{18} atoms cm^{-2} in each channel. The data were reduced using a modified version of the standard HIPASS reduction software[17] (which was designed for imaging discrete H I sources). The bandpass correction was calculated for each beam and velocity by breaking each 8° scan into five sections, finding the median emission in each section and using the minimum of the five values. This greatly increases our sensitivity to large-scale structure without significant loss of flux density, except near the Galactic Plane.

Figure 1 is a detailed image of the Magellanic System. This image shows the H I peak intensity distribution in a 2400 square degree mosaic, centred on the South Celestial Pole. Components such as the Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC), Magellanic Bridge, Galactic Plane and beginning of the Magellanic Stream are identified. The feature we wish to focus on here however, lies "between" the Clouds and the Galactic Plane and is labelled "Leading Arm". The Leading Arm is shown in more detail in the channel maps of Figures 2 and 3. Of particular interest is the connection of the Leading Arm to the Magellanic Clouds shown in Figure 2 and, despite its relative thinness ($\sim 1/4$ the width of the trailing Stream), the continuity of the Arm to at least Galactic latitude $b \sim -8°$. The link between the Magellanic System and the strong emission features at $(\ell, b) = (297°, -24°)$ and $(\ell, b) = (302°, -16°)$, is not visible in the earlier data of Mathewson & Ford[18] (their figure 2) or Morras[19], due to their sparse spatial sampling. Indeed, it is the lack of continuity in the earlier data that was offered as evidence for the absence of a leading arm[6,8].

The velocity distribution of the leading H I also suggests a continuous flow of material which originates from the Magellanic System. Figure 2 steps through the velocity channels from $v_{\rm lsr} = 171$ to 356 km s^{-1}. The H I emission is first seen at the position of the SMC and then continues into the Bridge and the LMC. There is subsequently a flow in velocity towards the Galactic Plane through the newly discovered Leading Arm, with the emission disappearing at $\sim$ 356 km s^{-1}. In this direction, $(\ell, b) = (300°, 0°)$, the maximum Galactic disk velocity allowed under the assumption of circular rotation is $\sim$ 120 km s^{-1} [20], in agreement with the observed upper limit[21]. The observed velocity of the Leading Arm ($\sim$ 310 km s^{-1}; see Figures 2 and 3), coupled with its velocity-space continuity with the Magellanic System, clearly eliminates the possibility of the material being associated with the Milky Way disk.

This continuous Leading Arm, extending $\gtrsim 25°$ from an area near the LMC towards the

Galactic Plane, is a natural prediction of tidal models[9–14]. The most sophisticated of such models to date[10] predicts an ~ 1.5 Gyr-old leading arm, with a mass $\sim 1/3$ that of the Stream, emanating from the SMC/Bridge region and spanning the region $\ell \approx 280°$ to $310°$ and $b \approx -30°$ to $+50°$. When considering the region $b < 0$ (i.e. the region shown in Figures 1 - 3), the mass of the predicted arm is $\sim 1/8$ that of the Stream, with a relatively flat velocity distribution and a deviation from the Great Circle defined by the trailing Stream of $\sim 30°$. Some care must be taken when directly comparing these model results with new observational data, as three-dimensional spatial information does not exist. Under the assumption of constant and equal distances, the mass ratio of the observed Leading Arm to the Stream is $\sim 1/25$. However, there is reason to believe that the tip of the Stream is closer than its head[11,12], implying that the inferred observed mass ratio obtained here is actually a lower limit. The velocity and projected orientation of the observed Leading Arm lie within ~ 50 km s^{-1} and $\sim 30°$, respectively, of that predicted by Gardiner and Noguchi[10]. This overall agreement is remarkable when you consider the simplifying assumptions employed and the limited parameter space covered (in particular, the shape of the LMC potential and the mass of the Galactic Halo). Our recognition of the missing leading arm feature emphasizes the need to advance current tidal models and address the remaining discrepancies.

The identification of a continuous Leading Arm to the Stream, of *at least* 25° in length, argues against the ram pressure model, but with two caveats. First, in any tidal model, stars are expected to be torn from the Magellanic System together with the gas, yet so far searches for stars associated with the Stream have been negative[15,22]. This may be due to previous searches not being sensitive to an enhancement of stellar populations older than the ~ 1.5 Gyr Stream age favoured by current tidal models[10,23]. More probably it is due to the initial gas distribution being significantly more extended than the stellar component as confirmed in interferometer studies of spiral galaxies[24], and as seen in other interacting systems[25]. A second caveat is that some ram pressure models form leading features[7,8]; but only at the expense of significantly worsening the predicted extent and velocity profile of the Magellanic Stream.

In Figure 4, we present an expanded view of the LMC/SMC system. This view is remarkable in showing the LMC to have a much more regular spiral structure in neutral hydrogen than it does optically[26]. There is also evidence for a thin tidal tail emanating from the LMC at $(\ell, b) = (284^\circ, -33^\circ)$ and extending into the Bridge region towards the SMC. Tentative evidence for such a tail has been presented before[27], but Figure 4 provides unequivocal evidence for such a tail and thus for a tidal interaction between the LMC and SMC. This is in addition to the evidence presented in Figures 1 - 3 for a tidal interaction between the Galaxy and the Magellanic System as a whole.

In the future, it will be interesting to determine the full extent of the Leading Arm. Does there exist a complete ring of Magellanic Cloud material? A recent metallicity determination[28] for a high-velocity cloud lying above the Galactic Plane at $(\ell, b) = (287^\circ, 23^\circ)$ suggests a Magellanic Cloud origin, possibly implying a greater extent for the Leading Arm. Exploring the velocity structure of the Leading Arm in more detail will also aid our understanding of the Milky Way's interaction with the Magellanic Clouds. These types of observations provide crucial constraints on simulations aimed at reproducing the formation and evolution of the Magellanic System. This remains one of the only extragalactic systems for which an approximate three-dimensional orbit has been measured and it is an invaluable probe of the mass and extent of the Galactic halo. A full understanding of the role of accretion and tidal interaction in this local "Rosetta Stone" is essential if we are to fully appreciate their effects in the Universe at large.

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Correspondence should be addressed to M.E.P. (e-mail putman@mso.anu.edu.au).

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Figure Captions

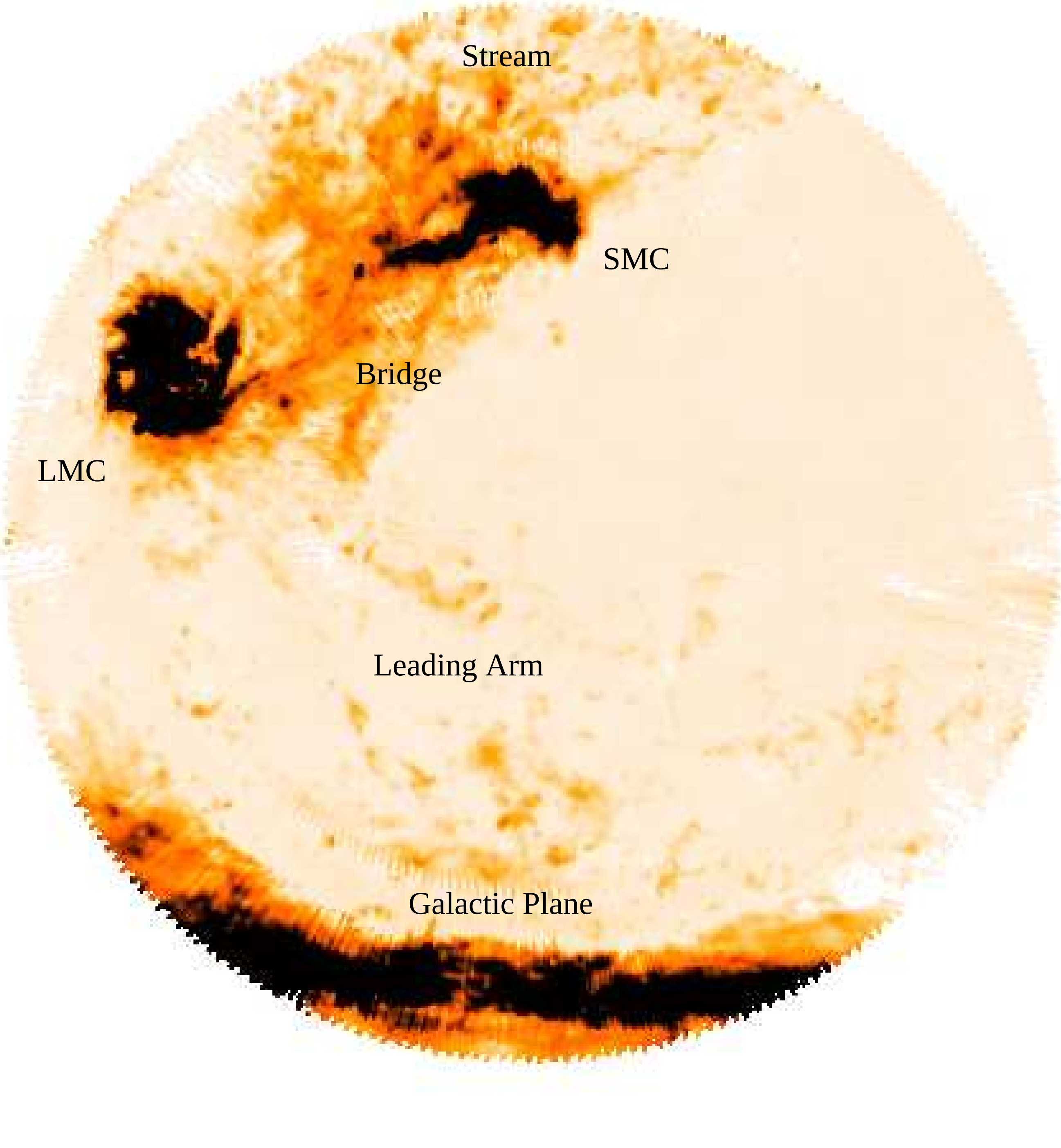
Figure 1. The 2400 square degree mosaic of the South Celestial Pole with the main features labelled, including the area containing the newly identified Leading Arm. The Stream extends 100° beyond its labelled starting point. This image is a peak neutral hydrogen intensity map using the first scans of HIPASS data (see text) in the velocity range $v_{\rm lsr} \approx 82$ to 400 km s^{-1}. Declination -90° is at the centre with the edge of the image extending to declination -62°. Right Ascension $0^{\rm h}$ is at the top of the figure and increases anticlockwise. Note the lack of H I emission in the region between the SMC and Leading Arm. Discontinuity of emission at the Galactic Plane is an artefact of the bandpass removal.

Figure 2. Channel maps of the Magellanic System as labelled in Figure 1. $v_{\rm lsr}$ is labelled in km s^{-1} in the left upper corner of each channel. Note the continuous flow of the H I emission starting from the SMC and moving into the Bridge, the LMC and finally, the newly discovered Leading Arm. The background striping is a result of the scanning method used for the HIPASS survey. The high positive velocity of the arm eliminates the possibility of stray radiation effects[29] and an association with material from the Milky Way disk[20,21]. For comparison, the Magellanic Stream extends from 100 km s^{-1} near the Clouds, to -200 km s^{-1} at its tip[4]. The orientation of this figure was chosen to match Figure 1.

Figure 3. A detailed view of the Leading Arm at the channel centred upon $v_{\rm lsr} = 323$ km s^{-1}. Contours are from 10 - 90% of the brightness temperature maximum ($T_{\rm B} = 0.88$ K). Contrast the continuous nature of the arm, with the previously assumed "discrete" nature of the H I in the Mathewson et al.[17] figure 2. The total H I mass of the Arm is $\sim 1 \times 10^7$ $M_\odot$, and it deviates from

the Great Circle defined by the trailing Stream by $\sim 60°$. Both the deviation angle and the H I mass are consistent with the model predictions of Gardiner & Noguchi[10]. The orientation of this figure was chosen to match Figure 1.

Figure 4. Expanded view of the LMC+SMC+Bridge regions from Figure 1. The LMC is at the bottom left, with the Bridge extending to the position of the SMC in the upper right of the figure. Note the emission filament emanating directly from the LMC (at $(\ell, b) = (284°, -33°)$) into the Bridge. This suggests that the Bridge may contain more mass from the LMC than was previously thought[11]. The orientation of this figure was chosen to match Figure 1.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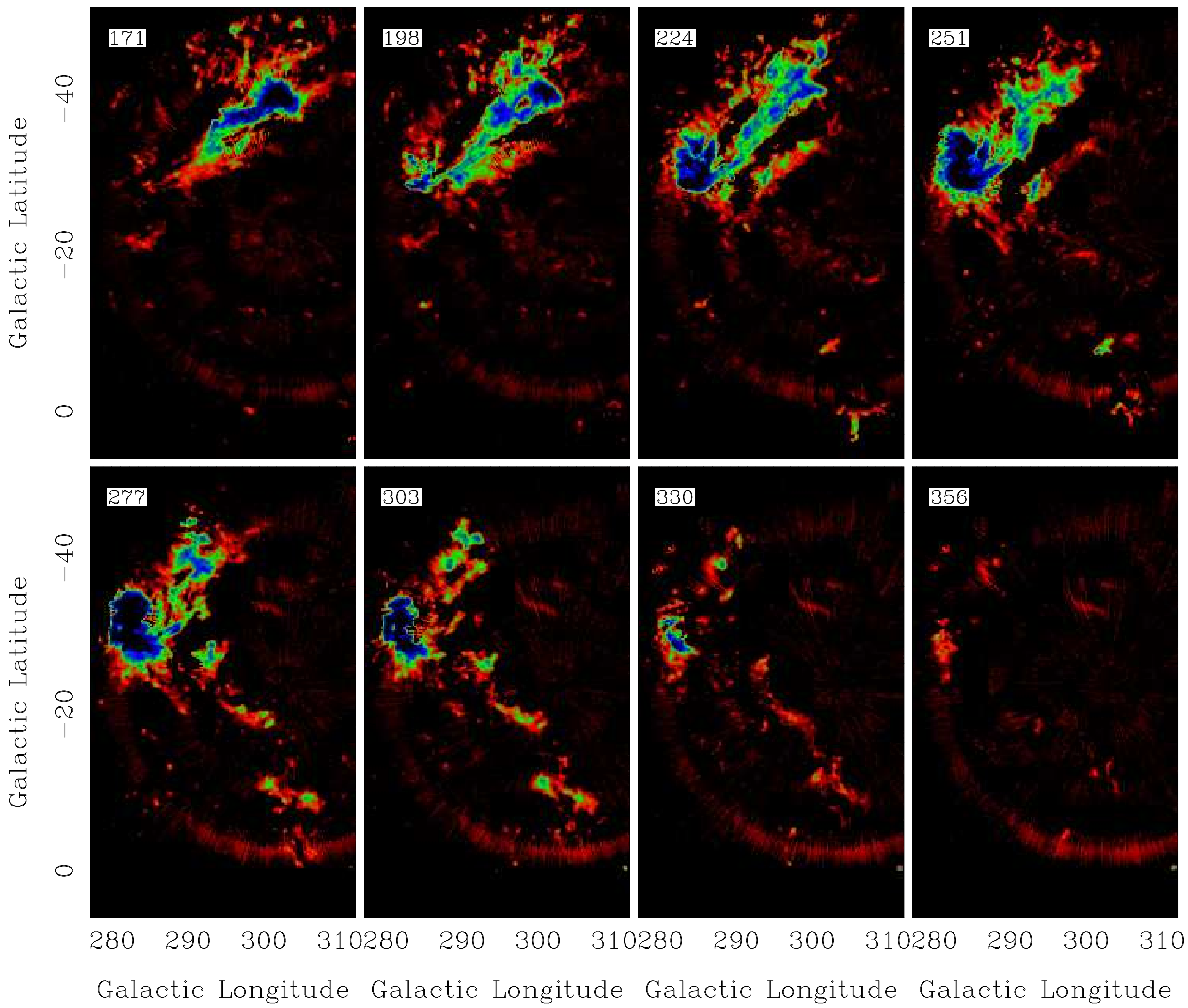
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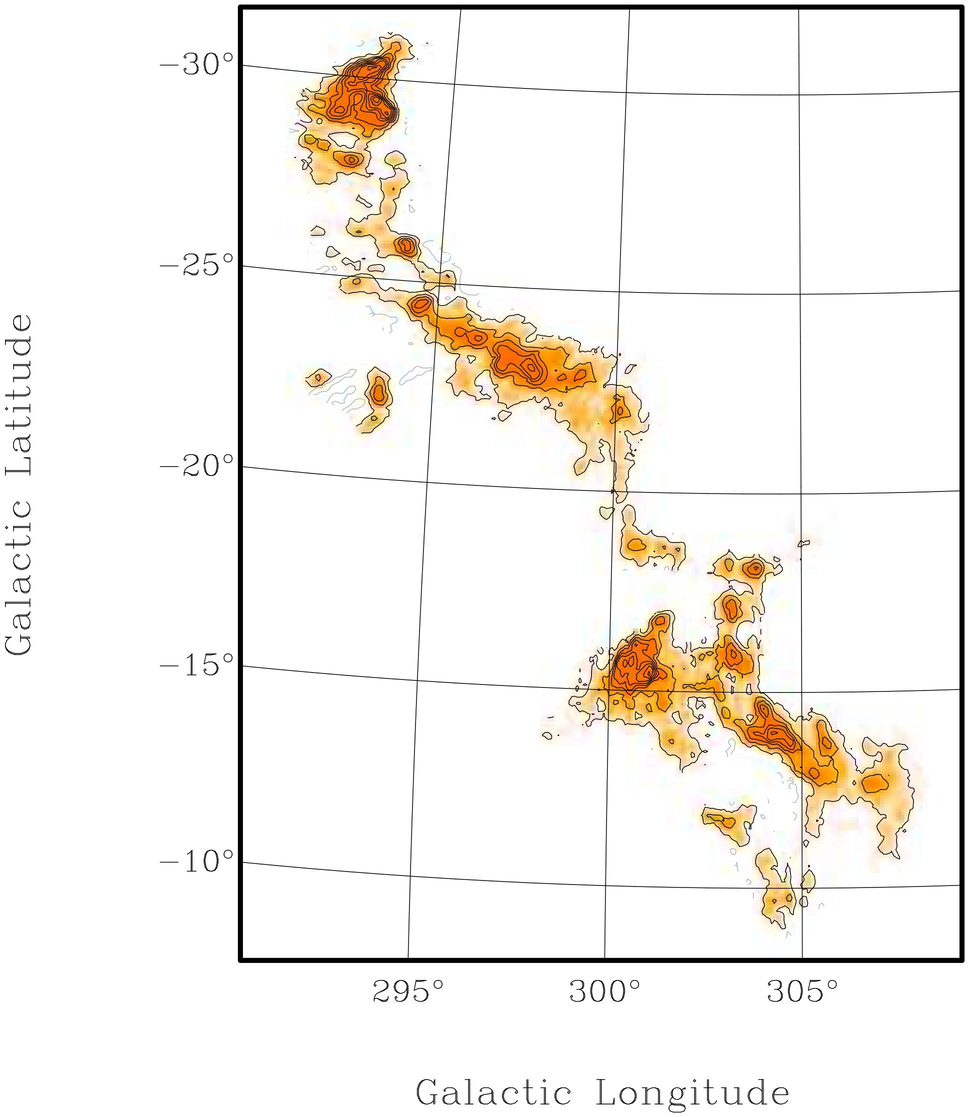

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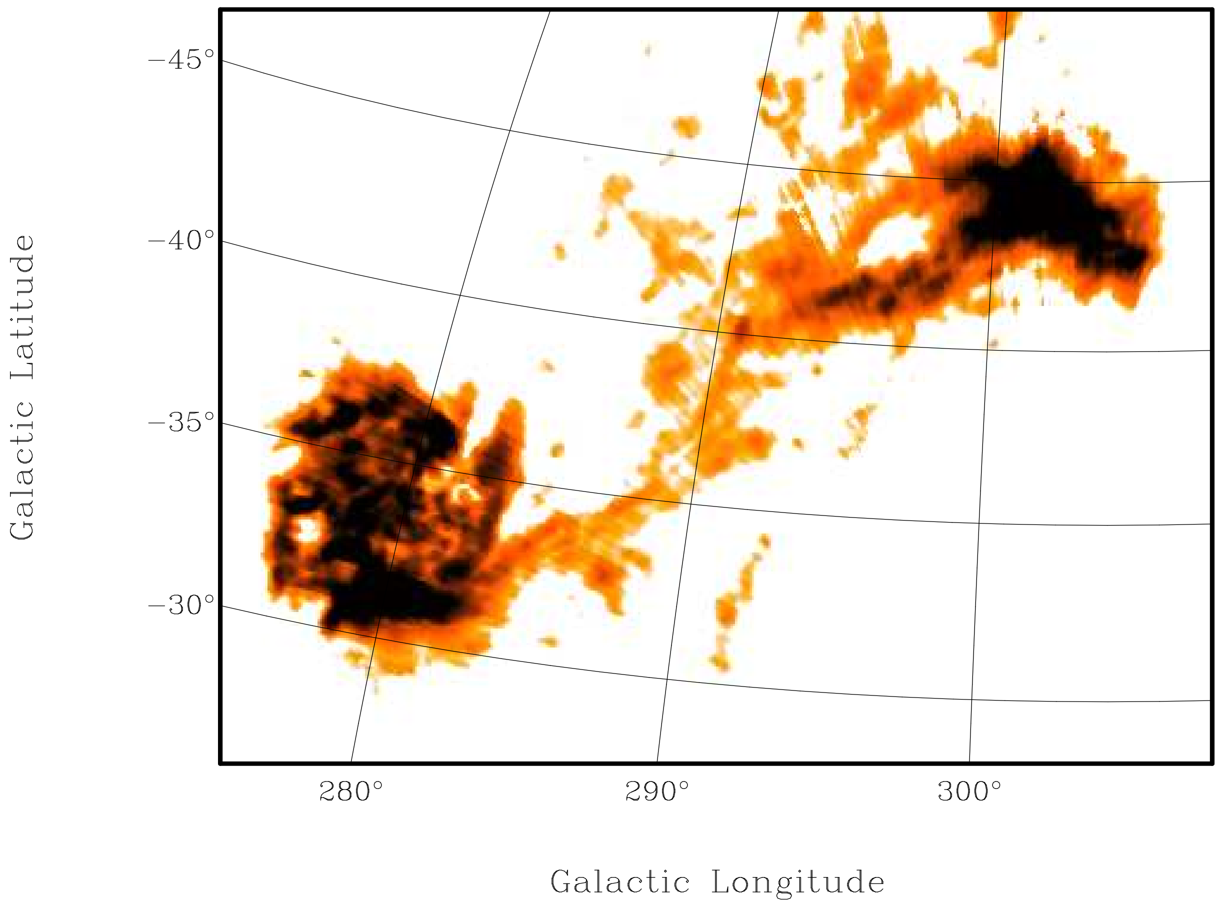

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