GALACTIC WORMS

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ABSTRACT. We have found and cataloged over 100 vertical structures in H I, infrared, and radio continuum emission. These correspond to the H I worms detected by Heiles (1984). The infrared and the radio continuum properties of worms suggest that some worms have associated ionized gas. The area filling factor of superbubbles in the inner Galaxy is estimated to be greater than ~0.1.

1. INTRODUCTION

Heiles (1984), in his pioneering study of H I shells and supershells, found interesting features in the inner Galaxy, 'H I worms'. By applying a median filter, which enhances small scale structure, to the H I channel maps near the Galactic plane ($|b| < 10°$), he found that the filtered structure appears to be random in the outer Galaxy, while in the inner Galaxy it tends to run perpendicular to the Galactic plane and individual features tend to persist over a large velocity interval. He interpreted these vertical structures, or H I worms, as the walls surrounding superbubbles, which have broken through the thin gaseous disk inside the solar circle.

In this paper we report a systematically determined catalog of 118 similar structures, not only in H I but also in the infrared and the radio continuum, and present some preliminary results.

2. OBSERVATIONS AND DATA ANALYSIS

The H I 21-cm maps between $10 \leq l \leq 350$ are made from the Galactic plane survey of Weaver and Williams (1973) and of Kerr *et al.* (1986). The missing data near the Galactic center were obtained using the Hat Creek 85-foot. The infrared 60 and 100 μm maps are made from the *IRAS Zodiacal Observation History File* (1988). The radio continuum maps are made from the 408 MHz survey of Haslam *et al.* (1982). All the maps have $0.°5 \times 0.°5$ pixel size, and a median filter of $3.°5 \times 3.°5$ was applied to see small scale structure near the Galactic plane ($|b| < 10°$).

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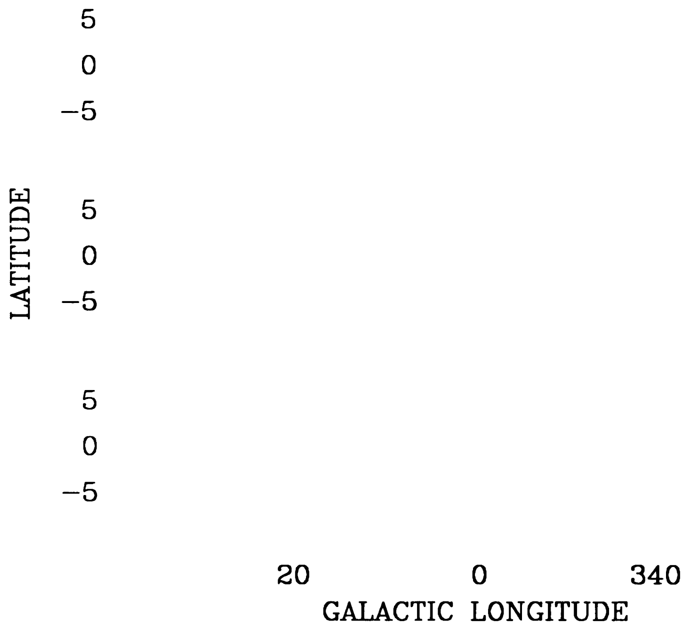

Figure 1. The median-filtered H I, 100 μm, and 408 MHz map (from top to bottom) in the inner Galaxy.

Figure 1 shows the median-filtered H I map integrated from −200 to +200 km s^{-1} in the inner Galaxy together with the corresponding 100 μm and 408 MHz maps as an example. The correlation between the H I and the 100 μm map is remarkable, which proves that most of these structures are real. By cross-correlating the 60 and 100 μm maps with the H I map, but excluding the very central region of the plane ($|b| < 1°$), we found a total of 118 isolated structures that are larger than 5 pixels and appear in both infrared and H I maps. The identification and the cross correlation of structures were made by 'unbiased' search technique based on a computer algorithm which will be described in a subsequent publication. We will call all 118 structures 'worms' even though some of them are small and at high latitudes, so that they are not worms in the sense that they do not 'crawl out of the Galactic plane'.

Not all the worms appear in 408 MHz emission. Among 118 worms, 35 have counterparts at 408 MHz.

3. INFRARED AND RADIO CONTINUUM PROPERTIES OF WORMS

Figure 2a shows the median value of the 60 to 100 μm intensity ratio, I_{60}/I_{100}, versus the median value of the 100 μm emissivity, $I_{100}/N_{\mathrm{H\,I}}$, of each worm (open circles). The ratio I_{60}/I_{100} is almost independent of $I_{100}/N_{\mathrm{H\,I}}$, although there may be a trend such that a worm with a larger $I_{100}/N_{\mathrm{H\,I}}$ has a larger I_{60}/I_{100}. This result is in good agreement with theoretical calculations of Draine and Anderson (1985). The average I_{60}/I_{100} of all worms is large 0.28 ± 0.06, and implies a grain size distribution with a relatively large number of smaller grains, which may be due to the population of shock-processed grains.

The large variation of $I_{100}/N_{\mathrm{H\,I}}$ is due to at least three factors: (1) the general increase of the diffuse interstellar radiation field toward the Galactic interior, (2) the worms with associated H II regions, e.g., GW6.5−3.7 (Galactic Worm centered at $l \approx 6.5$ and $b \approx -3.7$) with S25, GW14.9−1.6 with S45, GW17.8+3.0 with S54, and G31.6−5.9 with W43 in Figure 1, and (3) the worms with associated molecular gas, e.g., GW1.9+6.0 and GW19.5−6.4. The decomposition of the infrared emissivity into each contribution needs to be done for individual worm.

Figure 2b shows the average 408 MHz brightness temperature versus the average 60 μm intensity of each worm. There is a good correlation between the two. We are currently unsure of whether the 408 MHz continuum is thermal or nonthermal. One known example of nonthermal emission associated with H I is the North Polar Spur (Heiles *et al.* 1980), and a known example of thermal emission is GW17.8+3.0 (Müller, Reif, and Reich 1987). For the worms with associated H II regions, the 408 MHz emission is likely to be thermal. In Figure 2b, the straight line is an expected relationship for a diffuse H II region by assuming that all the Lyman α photons are converted to infrared photons. The apparent deficit of 60 μm emission possibly arises because some Ly α photons leak through the vertical direction. On the other hand, it may suggest that the 408 MHz emission is non-thermal.

4. SUMMARY AND DISCUSSION

We have found that there is a very good correlation between H I worms and infrared worms, and that many prominent worms have their counterparts at 408 MHz. We also found that some worms are very likely to have associated ionized gas, which needs to be confirmed by some direct observations, e.g., radio recombination lines.

One primary goal of this work is to answer the following question: "What is the filling factor of superbubbles in our Galaxy ?" We can make a very crude estimate based on our results. A superbubble that has broken through the *thin* gaseous disk occupies an area with radius comparable to or larger than the scale height ~ 190 pc. In the first and the fourth quadrant, there are about 30 worms that actually rise *from* the Galactic plane. If we assume that most worms within 4 kpc are detected, then the filling factor of the inner Galaxy is greater than ~0.1.

A superbubble that has broken through the thin gaseous disk does *not* necessarily

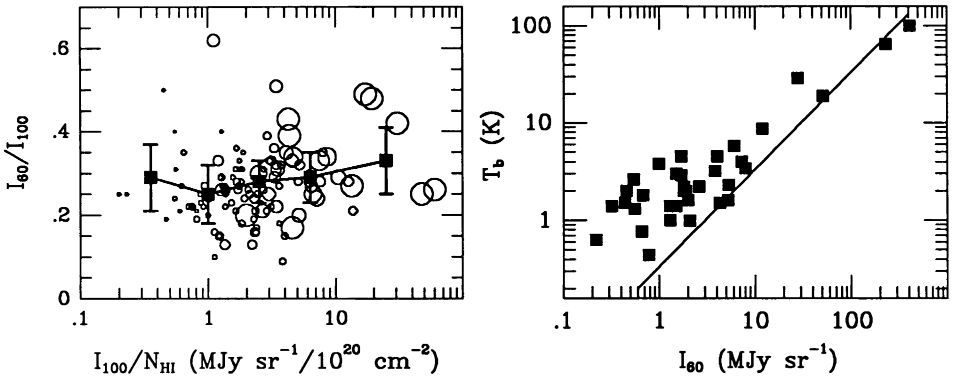

Figure 2. (a) The median value of I_{60}/I_{100} vs. the median value of $I_{100}/N_{\mathrm{H\,I}}$ of each worm (open circles). The area of the circle is proportional to the average 100 μm intensity. The average values per unit logarithmic interval are shown as squares with 1σ error bars. (b) The average 408 MHz brightness temperature vs. the average 60 μm intensity of each worm. The straight line is an expected relationship for a diffuse H II region.

inject hot gas into the halo, because there is a thick H I layer, and also a even thicker layer of ionized gas (Lockman 1984; Reynolds 1989). However, the cold fragments, which result from the Rayleigh-Taylor instability when the supershell accelerates, are likely to be injected into the halo. According to Mac Low *et al.* (1989), about 5% of the shell mass is in cold fragments, then, if we take 50 Myr as the characteristic lifetime of a superbubble, the filling factor of ~0.1 implies a mass injection rate of ~0.2 $M_\odot$/yr.

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