RADIO STUDIES OF THE DISTRIBUTION OF IONIZED GAS

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INTRODUCTION

Although radio recombination line and continuum observations are very useful for investigating galactic structure, it is well to remember their limitations. First, they only provide measurements of coordinates and velocities; a kinematic model is needed to derive the distance and thus the actual location of every nebula. In some directions, particularly all longitudes $\gtrsim 50°$ from $\ell=0°$, kinematic distance estimates are prone to systematic errors arising from velocity crowding or uncertainties in the rotation curve, and are of little use in quantitative studies. I will only discuss the distribution of radio nebulae in the inner $\sim 100°$ of the galactic plane, since in this area kinematic analyses can give reasonable results and, in any case, here we must rely on radio observations for most of our information.

The second limitation is that it is not easy to quantify the properties of the gas being observed at radio wavelengths. Surveys in different recombination line transitions are selectively sensitive to different components of the ISM. In addition, radiative transfer, antenna beam convolution and confusion effects can be so severe that meaningful estimates of the mass of ionized gas or even of the number of HII regions in the inner Galaxy are difficult to make. However, it is possible to distinguish between two types of nebulae that have been studied at radio wavelengths. The first are those observed in high frequency discrete-source surveys. I will call these "dense" nebulae since they were observed because they appeared as bright features against the galactic continuum; they are generally small, high emission measure objects. Dense HII regions are one of the few species which has been observed with complete latitude coverage and comparable sensitivity in both hemispheres. Secondly, there are lower frequency surveys made with relatively large antenna beamwidths which aim to cover a portion of the Galaxy in the manner of HI and CO surveys. These observations are most sensitive to large, moderate density nebulae, although to some extent they detect recombination line emission from the entire hierarchy of ionized structures along the line of sight.

W. B. Burton (ed.), The Large-Scale Characteristics of the Galaxy, 73–79.

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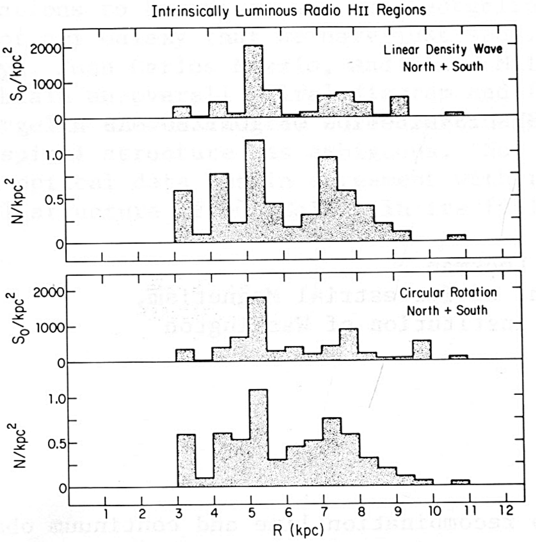

Figure 1: The surface density of dense radio HII regions vs. distance from the galactic center.

The basic radio data on ionized gas in the inner Galaxy come from the discrete source (H109α) surveys of Reifenstein et al. (1970) and Wilson et al. (1970) (supplemented by a few other observations, e.g. Dickel and Milne, 1972; Caswell, 1972), and from the uniformly-spaced lower frequency recombination line surveys of Hart and Pedlar (1976) and Lockman (1976). Our task is to convert these measurements into a function N(R,θ,z) which describes the amount of ionized gas at a given distance from the galactic center, azimuthal angle, and distance from the plane.

THE DISTRIBUTION OF DENSE NEBULAE

I have selected a set of 110 dense nebulae which 1) have longitudes in the range 5°≤ℓ≤55° or 305°≤ℓ≤355° (to be called the northern and southern intervals, respectively); 2) have accurate 5 GHz recombination line and continuum measurements; 3) have been observed in enough absorption species to allow resolution of distance ambiguities and 4) are intrinsically luminous in that each must be ionized by at least one O star. This set was analyzed using models based on circular motion and density-wave theory; full results are given elsewhere (Lockman, 1979). All of the nebulae lie within 15 kpc of the sun, so the following remarks refer mostly to the HII regions in the half of the Galaxy nearest the sun. Because of the longitudinal restrictions, the galactic nucleus is not included and the sample is incomplete at R>8.2 kpc.

Figure 1 shows radial surface density functions (not corrected for distance selection effects) for dense nebulae. In many ways

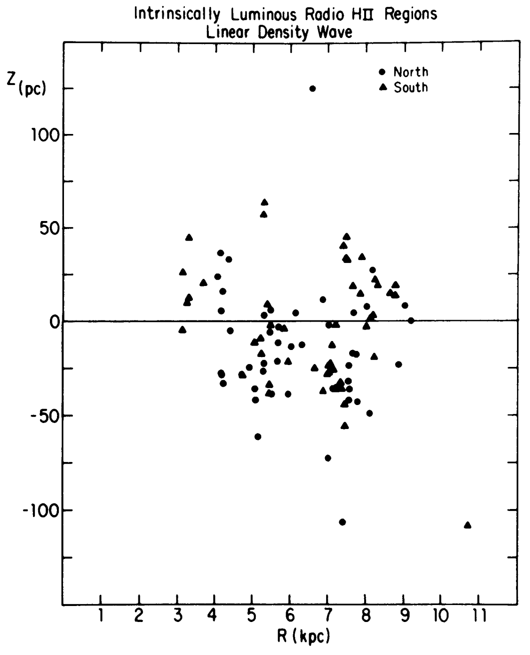

Figure 2: The distance of dense nebulae from the galactic plane, z, vs. their distance from the galactic center.

these are similar to previously published figures (Mezger, 1970). Both the number and absolute flux density (defined as the observed continuum flux density times the square of the source distance) per kpc^2 are shown; the latter quantity is a measure of the number of UV photons maintaining the ionization. Note the secondary peak in the surface densities near 7.5 kpc. This is not a feature in the N(R) functions of other population I-type species like CO and SNRs (Burton, 1976), whose radial abundance has fallen to quite low values at R=8 kpc. While the secondary peak may be partly an artifact of distance selection effects, it is unlikely that it is entirely so.

The inner boundary of dense nebulae is at R=4 kpc in the North and at R=3 kpc in the South (neglecting those at the galactic center). There is no compelling evidence that the 6 southern nebulae with R<4 kpc are in any way connected with the 3-kpc arm.

The distance of nebulae from the galactic plane is plotted vs. their distance from the galactic center in Figure 2. Although these results were derived from a linear density-wave analysis, the assumption of pure circular rotation produces little change in the distribution. Dense nebulae tend to lie in a well defined z(R) pattern. I have discussed this phenomenon elsewhere (Lockman, 1977), and it is seen in HI, CO, SNRs and OH/IR stars (Quiroga, 1974; Cohen and Thaddeus, 1977; Lockman, 1977; Bowers, 1978). The similarity of the pattern for northern and southern objects indicates

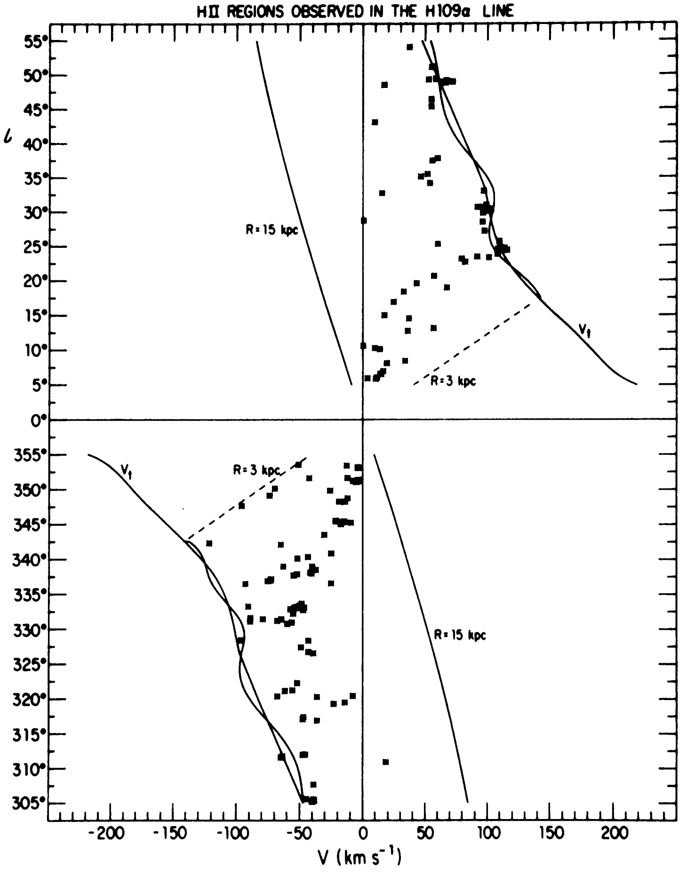

Figure 3: The observed velocities and longitudes of dense radio nebulae. This figure includes not only the intrinsically luminous nebulae, but fainter objects as well.

that the displacement from planarity is a large-scale characteristic of the Galaxy. The layer of dense HII regions has the smallest z-extent of any species: its mean z is -10 pc with a dispersion of only 30 pc; half the dense nebulae are located within 20 pc of the mean z.

The azimuthal distribution of dense HII regions cannot be derived from a simple plot of the nebulae in polar (R,θ) coordinates, for kinematic distance estimates are so uncertain that the appearance of a polar diagram is determined by kinematic assumptions as much or more than by the actual distribution of nebulae. Instead, the azimuthal distribution must be derived by comparing model distributions directly with the observations.

Figure 3 shows the sample of dense nebulae in the observed coordinates. Their v-ℓ distribution is singular among galactic

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species. Note the absence of nebulae near the terminal velocity (V_t) at ∿35° to 45° from ℓ=0° in both the North and South. These "gaps" along V_t are not seen in HI or CO and are unlikely to arise by chance, for projection of the galactic velocity field causes a rather large area in the Galaxy to have LSR velocities near the terminal velocity. (This effect, as pointed out by Burton, 1971, is the reason why HI profiles show a peak at V_t). The gaps along V_t are a distinctive feature of dense HII regions, and indicate that they have a distribution quite different from that of HI or molecular clouds.

Numerous calculations, using circular rotation, linear density-wave and nonlinear density-wave kinematics, show that the gaps along V_t are not produced in models with N(R,θ)=N(R). However, the gaps are reproduced if nebulae are located in a spiral pattern. The northern observations are matched by models with all nebulae confined to the vicinity of the two-armed spiral pattern derived by Burton (1971) from HI streaming motions. The Burton pattern was not intended to fit southern HI, and although use of it in models gives qualitative agreement with the southern nebulae, the "gaps" it produces are not at the correct longitudes. Models with the nebulae confined to rings also produce gaps along V_t, but these models fit the data better if the ring radius increases from North to South, i.e. in the sense of trailing spiral arms. These results are essentially independent of the adopted kinematic model. In sum, observations of dense nebulae are consistent with a confinement of nebulae to a spiral pattern, although there are too few data to allow accurate specification of the pattern. There is no compelling evidence for the existence of any interarm dense nebulae.

MODERATE DENSITY IONIZED GAS

Moderate density ionized gas is seen in very weak H166α recombination line emission at all positions in the plane with $\ell \lesssim 45°$. Because there have been no southern hemisphere observations and the northern surveys have been made almost entirely at b=0°, relatively little is known about this medium. It is possible that the H166α emission arises in large structures with emission measures $\sim 10^3$ cm^{-6} pc. Although this moderate density gas is abundant in the inner Galaxy, it has a smaller radial and longitudinal extent than the dense HII regions. It's N(R) function has no secondary peak near 7.5 kpc (Lockman, 1976; Hart, 1977), and its abundance has fallen below the detection level ∿8 kpc from the galactic center. Estimates of its scale height give dispersions ranging from 30 to 70 pc about z=0; I have made recent scans in H127α which generally support the smaller value, but which indicate that the scale height may vary.

Figures 2 and 3 in the review by Hart (1977) show an absence of H166α emission along V_t at the longitude of the northern "gap" in dense nebulae, indicating that moderate density ionized gas may

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be confined to the spiral pattern suggested by dense HII regions. However, there may well be some weak H166α emission in areas of the v-ℓ diagram lacking dense HII regions; the question of weak "interarm" HII regions cannot be decided without more sensitive observations. Except in the direction of the galactic center, northern data show no H166α emission at the velocity of the 3-kpc arm. It is reasonable to assume that, except for their more restricted radial abundance, low density nebulae are distributed like their dense counterparts.

CONCLUDING REMARKS

Dense galactic HII regions have a unique distribution. They have the smallest known scale height; they are found to within 3 rather than 4 kpc from the galactic center; they are the only known species which may be totally confined to a spiral pattern. Lower density nebulae are potentially more important than their dense counterparts as tracers of star formation, but their radio emission is so weak that, despite a substantial commitment of telescope time, relatively little is known about them. Existing data indicate that, except in their radial extent, they are distributed like the dense nebulae.

A model consistent with all recombination line observations from the inner Galaxy places all dense HII regions in trailing spiral arms (which, in the North, are identical to those derived by Burton, 1971), of extremely thin z-extent, located with or embedded in larger clouds of lower density ionized gas. It is likely that dense HII regions have a broader radial distribution than other species.

REFERENCES

Bowers, P.F.: 1978, Astron. Astrophys. 64, pp. 307-318.
Burton, W.B.: 1971, Astron. Astrophys. 10, pp. 76-96.
Burton, W.B.: 1976, Ann. Rev. Astron. Astrophys. 14, pp. 275-306.
Caswell, J.L.: 1972, Aust. J. Phys. 25, pp. 443-450.
Cohen, R.S. and Thaddeus, P.: Astrophys. J. 217, pp. L155-L159.
Dickel, J.R. and Milne, D.K.: 1972, Aust. J. Phys. 25, pp. 539-544.
Hart, L. and Pedlar, A.: 1976, Mon. Not. Roy. Astron. Soc. 176, pp. 547-559.
Hart, L.: 1977, in H van Woerden (ed.), "Topics in Interstellar Matter", Reidel, Dordrecht.
Lockman, F.J.: 1976, Astrophys. J. 209, pp. 429-444.
Lockman, F.J.: 1977, Astron. J. 82, 408-413.
Lockman, F.J.: 1979, Astrophys. J. (in the press).
Mezger, P.G.: 1970, in W. Becker and G. Contopoulos (eds.), The Spiral Structure of Our Galaxy", Reidel, Dordrecht.
Quiroga, R.: 1974, Astrophys. Space Sci. 27, pp. 323-342.
Reifenstein, E.C., Wilson, T.L., Burke, B.F., Mezger, P.G. and Alterhoff, W.J.: 1970, Astron. Astrophys. 4, pp. 257-377.
Wilson, T.L., Mezger, P.G., Gardner, F.F. and Milne, D.K.: 1970, Astron. Astrophys. 6, pp. 364-384.

DISCUSSION

Cohen: The b = 0° CO ℓ,v map is very similar to the HII distribution you have shown. Also, the radial distribution of CO shows a small peak at 7 kpc from the galactic center.

Lockman: Although CO ℓ,v diagrams may show "gaps" along the terminal velocity at certain latitudes, the surface density of CO is rather uniformly distributed along v_t. This is not the case for the dense HII regions.

Roman: What distance did you use for the Sun's distance to the galactic center?

Lockman: R_o = 10 kpc.

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