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NOTE ON THE DENSITY OF IONIZED HYDROGEN IN THE GALACTIC SYSTEM

BY GART WESTERHOUT

It is shown that the density and total mass of ionized hydrogen in the Galactic System derived in Chapter 7d of the preceding article are upper limits. If part of the brightness temperature of the thermal component of the galactic ridge is due to bright and dense nebulae rather than to faint emission regions, the average density of ionized hydrogen and its total mass may be considerably lower.

In this note some comments are made on the derivation, in the preceding article (WESTERHOUT 1958), of the density and total mass of the ionized hydrogen. The numbers of figures, tables and chapters mentioned refer to that article. The note should be considered as an appendix to the preceding article, and thus no explanation will be given of the terms and methods used.

Figure 15 gives the brightness temperature of the thermal component of the galactic radiation along the galactic ridge as a function of galactic longitude. This function forms the basis of a circularly symmetric model of the distribution of thermal volume emissivity throughout the Galactic System. This distribution is tabulated in the second column of Table 14 as the value of the brightness temperature T_i^{1390} per kpc, which may be identified with 10^4 times the optical depth per kpc:

$$10^4 \tau / \text{kpc} = T_i^{1390} / \text{kpc}.$$

(In the following we shall omit the superscript 1390). In the calculations of the density distribution in the further columns of Table 14 it is assumed that this brightness temperature is entirely due to the integrated radiation of many faint emission regions having hydrogen densities of 5 to 10 cm^{-3} .

Two objections may be raised to this derivation. First, the function in Figure 15 may be traced back to Figure 7, where the lower envelope to the observed brightness temperature along the galactic ridge has been drawn, which envelope has been separated into the thermal and nonthermal components in Figure 13. Hence, a certain number of apparently bright sources was omitted in the discussion and we still have to investigate whether the many thermal sources among them add noticeably to the average density of ionized hydrogen in the galactic plane. Secondly, the identifications showed that some of these sources are very dense and intrinsically very bright objects; we may thus wonder whether the adopted $N = 5$ or 10 cm^{-3} in Table 14 are not too conservative and whether allowance should be made for a certain proportion of denser regions.

Regarding the first question we may say that it would not be justified to include all the discrete sources in Figure 7 in a smoothed curve, for the basis

of the separation of thermal and nonthermal components would then be lacking. This separation is performed by comparing with roughly the same resolving power two values of the brightness temperature at different frequencies, measured at the same part of the sky, chosen so that it does not include apparently bright sources. The best procedure would be to use the combined brightness of the thermal sources and the thermal background radiation in the calculation of the density. In that case, the thermal brightness and hence the density of ionized hydrogen would be increased about 30 per cent. This value decreases again if the effective value of N is higher than 10 cm^{-3} . This depends on the relative number and density of the high-density nebulae. An attempt at a more precise determination has necessarily to start with a discussion of the individual bright sources and their identifications.

We shall first consider the sources in the region $l = 320^\circ - 10^\circ$, in which region the separation of thermal and nonthermal radiation, on which the density distribution is based, was made. Excluding a few doubtful sources, extended regions Nos 26, 36 and 45, Sgr A, and the blend of a thermal and nonthermal source, No 28, we have a total of 19 thermal sources with a flux density of $4200 \times 10^{-26} \text{ Watt/m}^2(\text{c/s})$. The flux density of the thermal ridge in this region may be calculated from the relation

$$S = 17.9 \times 10^{-26} \int T_b d\Omega, \quad (1)$$

where $d\Omega$ is given in square degrees. We find a value of roughly $15.000 \times 10^{-26} \text{ Watt/m}^2(\text{c/s})$, which is only 3.5 times the flux density of the bright sources. The 8 sources of which the distance is known have a flux density of 3000×10^{-26} and an average distance $r = 1.45 \text{ kpc}$, while they are concentrated in a layer of roughly 50 pc thickness. Seven more sources are identified with emission nebulae of which r is unknown, or are situated in a region with strong foreground obscuration. It seems reasonable to assume that these, like the sources with known r , also have $r < 2 \text{ kpc}$. The 15 sources with $r < 2 \text{ kpc}$ have a total flux density of 3900×10^{-26} , while their average flux density at unit distance $r = 1 \text{ kpc}$ is $\bar{S}_1 (r = 1 \text{ kpc}) = 550 \times 10^{-26} \text{ Watt/m}^2(\text{c/s})$. We shall, however, exclude source No 38, the Omega nebula,

from our further calculations, as this source is extraordinarily bright compared to all other thermal sources found in the present survey, having S_1 ($r = 1$ kpc) = 3000×10^{-26} . In that case, the average flux density at 1 kpc $\bar{S}_1 = 330 \times 10^{-26}$ and the total flux density of the 14 sources with $r < 2$ kpc is 2800×10^{-26} . It was assumed in Chapter 7d that the thermal background radiation is caused by a large number of faint emission regions, with $E = 400 - 800$ cm⁻⁶ pc, diameters between 5 and 30 pc and densities between 5 and 10 cm⁻³. A typical cloud of this kind has S_1 (1 kpc) = 5×10^{-26} Watt/m²(c/s). We are now considering clouds that are intrinsically very bright as compared to such a faint emission region.

We shall now calculate the brightness temperature T_b which may be expected from a number of bright sources, all with the same absolute brightness, having a space density $p(r)$ kpc⁻³. The number of sources per square degree on the sky, at a distance r ($r > 2$ kpc) along 1 kpc of line of sight, is approximately $3.05 \times 10^{-4} r^2 p(r)$. If the flux density of one source at $r = 1$ kpc (i.e. the absolute brightness) is S_1 , their total flux density is $S = 3.05 \times 10^{-4} p(r) S_1$. From (1), taking $d\Omega = 1$, we find

$$T_b/\text{kpc} = 0.17 \times 10^{-4} p(r) S_1 \times 10^{26}. \quad (2)$$

The space density of the 14 sources with $\bar{S}_1 = 330 \times 10^{-26}$ and $r < 2$ kpc is $p(r) = 160$ kpc⁻³. Assuming that the space density has this value throughout the hydrogen layer, and that $S_1 = \bar{S}_1 = 330 \times 10^{-26}$, we find for a line of sight of 15 kpc, $T_b = 14$ °K. This is roughly 1.4 times the average observed value of T_b in the region $l = 320^\circ - 10^\circ$. The value of $p(r)$ used is the value near the sun. One would expect it to increase towards the galactic centre, so that the calculated value of T_b would become even higher. Apparently we have either overestimated S_1 , or the value of $p(r)$ near the sun is much larger than the average value at larger distances.

Inspection of Figure 9 and Figure 4 shows that the density of bright sources in the region $l = 320^\circ$ to 10° is considerably greater than in the region $l = 10^\circ$ to 200° . If we consider the 10 thermal sources with $I > 30$ units, for which the survey is complete over the whole sky, we find that only four of these are situated in the latter region and that the region $l = 320^\circ$ to 10° is overpopulated by a factor of 6. Since 15 of the 19 sources in this region have distances between $r = 1$ and $r = 2$ kpc, it seems that we are confronted here with a concentration of bright sources along approximately 2 kpc of the Sagittarius arm.

The Cygnus complex seems to be a similar concentration. In a small area of sky, both the background intensity and the number of bright sources are considerably higher than in the surrounding region. Most of the bright sources are distributed

along 1.5 kpc of the Orion arm. The total flux density of these sources is 1930×10^{-26} Watt/m²(c/s) (excluding source No 66 which might be situated in the Perseus arm). It is difficult to estimate the thermal background temperature, since separation into a thermal and a nonthermal component is not possible through lack of high-resolution observations at a low frequency. If we assume that half the background temperature in the Cygnus complex has a thermal origin (which is about the same as in the region $l = 320^\circ - 10^\circ$) the total flux density of the background is 1500×10^{-26} , i.e. of the same order as that of the bright sources. On the basis of our simplified model, we expect a flux density of this region of the order of 500×10^{-26} . From this observation we might conclude that not only the bright sources, but also the faint emission regions are more numerous than is normal at this distance from the centre. If also in the region $l = 320^\circ - 10^\circ$ in the Sagittarius arm, the background radiation has the same flux density as the bright sources, it follows from equation (1) that about 2.5 °K of the ridge temperature is caused by the concentration in this arm. Thus, it is quite possible that the high values of T_b around $l = 350^\circ$ are due to a local concentration in the Sagittarius arm, or perhaps even in an arm closer to the galactic centre.

Obviously, the assumption of axial symmetry, made in the derivation of the density distribution, is only a very crude approximation. The high density found near $R = 3.5$ kpc, for example, may well be highly exaggerated.

Until better data on the absolute flux density S_1 , and the space density $p(r)$ of the bright sources are known, any model must necessarily be very uncertain. The value of $p(r)$, for example, is practically unknown. Although it appears that the region $l = 320^\circ$ to 10° is strongly overpopulated, the factor of overpopulation can hardly be determined from 10 sources. The bright emission nebulae in the solar neighbourhood are concentrated in a layer of 50 pc thickness. The thickness of the layer of ionized hydrogen derived from the present survey (Chapter 7d) is 200 pc. Since this thickness is mainly determined by the denser inner parts of the Galactic System, it may well be that the value near the sun is just a local value. If we took 200 pc to be the thickness near the sun, we would find $p(r) = 42$ kpc⁻³.

We shall now calculate the average space density of ionized hydrogen in a new model, which takes into account the existence of bright sources. We may divide the brightness temperature per kpc of line of sight, given in the second column of Table 14, into two parts, one being due to faint emission regions and the other to bright sources. Assuming that the space distribution of both parts is the same, and that the bright sources have a flux density S_1 at 1 kpc and a

number density $p(r)$ per kpc^3 , we have with (2)

$$T_i(r)/\text{kpc} = (c + 0.17 \times 10^{-4} \times S_1 \times 10^{26}) p(r). \quad (3)$$

The first term on the right-hand side refers to the faint emission regions, the second term to the bright sources. The value of c may be derived from the values near the sun. From Table 14 we find that in the region concerned, T_i/kpc is approximately 0.4°K . Making the fairly arbitrary assumptions $p(r) = 30$ and $S_1 = 330 \times 10^{-26}$, we obtain $c = 0.0077$. Upon substitution of the numerical values into (3) we have

$$T_i(r)/\text{kpc} = (0.0077 + 0.0056) p(r).$$

Hence 42 per cent of the brightness in this model is due to the bright sources and 58 per cent to the faint emission regions.

With these figures and the data in the second column of Table 14 we can now calculate the total average space density in the new model. If a fraction α_i of space is occupied by ionized clouds, with a density of N_i per cm^3 inside each cloud, the average space density in a unit volume is $n = \sum \alpha_i N_i$. The brightness temperature per kpc of line of sight (or volume emissivity) is

$$T_i(r) = \frac{1}{538} \int_0^{1000 \text{ pc}} N^2 ds = \frac{1}{538} \overline{N^2} \times 10^3$$

$$= \frac{10^3}{538} \sum \alpha_i N_i^2 = \frac{10^3}{538} n \cdot N_{\text{eff}}, \quad (4)$$

$$N_{\text{eff}} = \frac{\sum \alpha_i N_i^2}{\sum \alpha_i N_i}. \quad (5)$$

In the case of one kind of clouds, $N_i = N$ and $N_{\text{eff}} = N$, and equation (4) reduces to equation (36) in the preceding article. In that article, we made calculations for two values of N for the faint emission regions. The bright sources around the sun have an average hydrogen density $N = 40 \text{ cm}^{-3}$. With two kinds of sources, taking $N_1 = 5$ and $N_2 = 40$, and remembering that $\alpha_1 N_1^2 / \alpha_2 N_2^2 = 77/56$, we find $N_{\text{eff}} = 8.0 \text{ cm}^{-3}$. With $N_1 = 10$ and $N_2 = 40$, the result

is $N_{\text{eff}} = 14.5 \text{ cm}^{-3}$. Thus, the total average space densities n for the new model are about 65% of the space densities given in Table 14. Also, the total mass of the ionized hydrogen decreases to 65% of the values given in Table 16.

The contribution of the bright sources to the average space density and to the total mass is between 8% ($N_1 = 5$, $N_2 = 40$) and 15% ($N_1 = 10$, $N_2 = 40$), although these sources are responsible for 42% of the brightness temperature.

We may put limits to the value of the total mass of ionized hydrogen. If the region $l = 320^\circ - 10^\circ$ contains no further bright sources besides the ones that were individually observed, the mass will be between 8.4 and $4.2 \times 10^7 M_\odot$ as derived in Chapter 7d, since the contribution of these sources to the total mass is negligible. On the other hand, if the ionized hydrogen is entirely concentrated in bright sources, the total mass is of the order of $10^7 M_\odot$. Both these situations are improbable extremes, and a conservative estimate of the total mass of ionized hydrogen would be $4 \times 10^7 M_\odot \pm 50\%$.

This whole calculation is dependent on the value of N_{eff} , i.e. on the distribution of ionized hydrogen in a volume of space. More sophisticated calculations, introducing more than two kinds of clouds, will be in order when more data about individual hydrogen clouds will be available. Such data may be obtained by means of observations with a narrower beamwidth, and preferably at a higher frequency, where nonthermal radiation plays a smaller part. More detailed optical observations, as well as distance determinations, are also urgently needed.

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REFERENCE

G. WESTERHOUT 1958, *B.A.N.* **14**, 215 (No. 488).