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RADIO ASTRONOMY EXPLORER-1 OBSERVATIONS OF THE GUM NEBULA

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Low frequency radio waves propagating in the interstellar medium are attenuated due to free-free absorption by thermal electrons in regions of interstellar H II. This process is so efficient that at frequencies below 1 MHz ($\lambda > 300$ m) one reaches unit optical depth at a distance of only a few hundred parsecs along a typical line of sight. Since the free-free absorption coefficient is a function of the density and temperature of the thermal electrons along the line of sight, one can attempt to use measurements of low frequency radio wave absorption to study the properties of the ionized component of the interstellar medium.*

When Brandt et al. (1971) proposed that the Gum Nebula should appear as an object subtending an angle as great as 90° in the galactic plane with an average electron density of about 0.16 cm^{-3} it became obvious that free-free absorption effects should occur in the nebula. Such a region should appear on low frequency radio continuum maps of the southern sky as an area of relatively low brightness since much of the background galactic synchrotron radiation coming from beyond the nebula should be absorbed by the ionized gas in the nebular region. If one could construct a spectrum of the nonthermal radiation coming from the direction of the Gum Nebula and detect the expected absorption, then it should be possible to measure the average optical depth over the nebula.

The optical depth for free-free absorption is given by

$$\tau_\nu = \frac{3.1 \times 10^4 \langle n_e^2 L \rangle}{T_e^{3/2} \nu^2} \left[3.9 + \ell n \frac{T_e^{3/2}}{\nu} \right]$$

where ν is the radio frequency in MHz, $\langle n_e^2 L \rangle$ is the emission measure in cm^{-6} pc, and T_e is the electron temperature in °K. Since the emission measure of the Gum Nebula can be estimated independently, a measurement of τ provides an estimate of T_e.

*The results presented in this paper appear in condensed form in Alexander et al. (1971).

Although this procedure is simple in principle, its utility is tempered by a number of complicating factors. For example, in compiling an average spectrum for the Gum Nebula one has to take into account the radiation from the supernova remnants in the direction of the nebula which are likely to have a different spectrum from the background radiation from the nebular region. Fortunately, the supernova remnants subtend a solid angle of less than ~10 sq. deg., and therefore they occupy a very small fraction of the total area of the nebula. By using radio surveys of high angular resolution the average spectrum of the galactic synchrotron radiation from the direction of the nebula can be estimated while minimizing the contributions due to the discrete supernova remnant sources.

A second complicating factor in the analysis of the spectrum arises from the fact that the absorption law for radiation originating from beyond the nebula will differ from that for radiation generated within the nebula. Galactic background radiation generated at distances greater than about 900 pc will be absorbed by a factor $e^{-\tau}$. Radiation by cosmic ray electrons that lie within the nebula in the same region as the absorbing thermal electrons will be attenuated by a factor $(1 - e^{-\tau})/\tau$. Uncertainties in estimating the relative contributions of these two components to the total spectrum will place a corresponding uncertainty on the optical depth derived.

A third complicating factor is the Razin effect, which results in a low-frequency cutoff to the spectrum of synchrotron radiation by particles in a thermal plasma. Such is the case for the component of nonthermal radiation by cosmic ray electrons in the highly ionized gas in the Gum Nebula. For a magnetic field $B \simeq 2\ \mu G$ and an electron density $n_e \simeq 0.18\ cm^{-3}$, the frequency of the Razin effect cutoff (corresponding to an effective Razin effect optical depth of unity) will be

$$\nu_R \simeq \frac{20\, n_e}{B} = 1.8\ \text{MHz}.$$

Hence the spectrum of the radiation component from within the nebular radius will be likely to fall off at low frequencies more rapidly than if free-free absorption alone were important.

The net result of the complicating factors mentioned above is to cause a tendency to over-estimate the amount of absorption occurring in the nebula, and hence we can only get an upper limit to the optical depth. Consequently, we determine a lower limit to the temperature of the region.

The average spectrum for the Gum Nebula region at low radio frequencies is shown in Figure 1. The brightness at each frequency was obtained by averaging the observed brightness distribution given in continuum maps over the region $240° < \ell < 280°$, $-15° < b < 15°$. The error bars shown are generally larger than the absolute uncertainty of the original published surveys and reflect the additional uncertainty due the averaging process and the removal of the supernova remnant radiation. A list of the surveys used to compile the spectrum and their angular resolution (antenna beamwidth) is given in Table 1.

Table 1
Southern Sky Surveys Used to Compile
Gum Nebula Spectrum

Frequency	Beam Size	Reference
150 MHz	2.2° × 2.2°	Landecker and Wielebinski (1970)
85	3.5° × 3.8°	Yates (1968)
55	14°	Rohan and Soden (1970)
30	11°	Mathewson <u>et al.</u> (1965)
18.3	17°	Shain and Higgins (1954)
6.55	14° × 34°	RAE-1
4.7	3° × 11°	Ellis and Hamilton (1966)
3.93	23° × 52°	RAE-1
2.1	7°	Reber (1968)

The points at 3.93 and 6.55 MHz were obtained from measurements with the Radio Astronomy Explorer-1 satellite. The brightness values were obtained by using maps produced by the RAE 229-m travelling-wave V antenna calibrated by absolute measurements of the average sky brightness with the satellite's 37-m dipole antenna. Details of the RAE-1 instrumentation are discussed by Weber et al. (1971). The brightness values at 2.1 and 4.7 MHz were obtained by normalizing to the values observed at high latitudes and calibrating with the absolute spectral data from RAE. Both the satellite measurements and the two lowest-frequency ground-based surveys at 2.1 and 4.7 MHz distinctly show regions of low brightness approximately centered on the Gum Nebula. This is illustrated in Figure 2 which shows a map of the region at 3.93 MHz from RAE-1. The fact that the center of the "low" in the isophotes is shifted to slightly smaller longitudes than the center of the nebula is probably due to beam-smearing effects arising from the presence of a second nearby H II region located at $\ell \approx 200°$, $b \approx -20°$. Although its size and shape cannot be unambiguously determined from the satellite measurements, the Gum Nebula region is one of the most pronounced features in the sky observed with RAE-1. That this is so is indicative of the very large area that must be subtended by the diffuse ionized gas associated with the nebula.

As one can see from Figure 1, the brightness in the direction of the nebula is down by about a factor of three at $\nu = 4$ MHz from a straight-line extrapolation of the high frequency emission spectrum. At 2 MHz the brightness would appear to have fallen by a factor of ~ 8. After making allowance for the difference in the form of the absorption law for foreground and background radiation and for the possibility of a Razin effect cutoff at $\nu \sim 2$ MHz, we estimate that the average optical depth for the nebula at 4 MHz is

$$\tau_4 \lesssim 3 \pm 1 .$$

The average electron temperature of the nebula corresponding to $\tau_4 = 3$ is shown as a function of emission measure in Figure 3. If we take the average emission measure of the visible filaments estimated by Brandt et al. (1971), $\langle n_e^2 L \rangle = 1300$ cm^{-6} pc, then the lower limit to the temperature of the nebula is $(5.7^{+1.8}_{-1.0}) \times 10^4$ °K. If, instead, we estimate the emission measure by using the value of $\langle n_e \rangle$ obtained from the pulsar dispersion measures and typical values of the clumpiness in H II regions such as the Orion Nebula (Spitzer 1968), we find $\langle n_e^2 L \rangle \approx 900$ cm^{-6} pc which gives $T_e \gtrsim 4.5 \times 10^4$ °K. As an extreme case, one could argue that the visible, high-density filaments occupy such a small fraction of the total area of the nebula that one should use the electron density derived from the pulsar dispersion measures to estimate the average emission measure implying a nearly uniform electron distribution. Then, $\langle n_e^2 L \rangle \simeq 25$ cm^{-6} pc and $T_e \gtrsim 4 \times 10^3$ °K. This number, of course, is the absolute lower limit to the nebular temperature. We are led to conclude that the average emission measure for the Gum Nebula is most probably $\gtrsim 600$ cm^{-6} pc so that for $\tau_4 \lesssim 3 \pm 1$, $T_e \gtrsim (4 \pm 1) \times 10^4$ °K.

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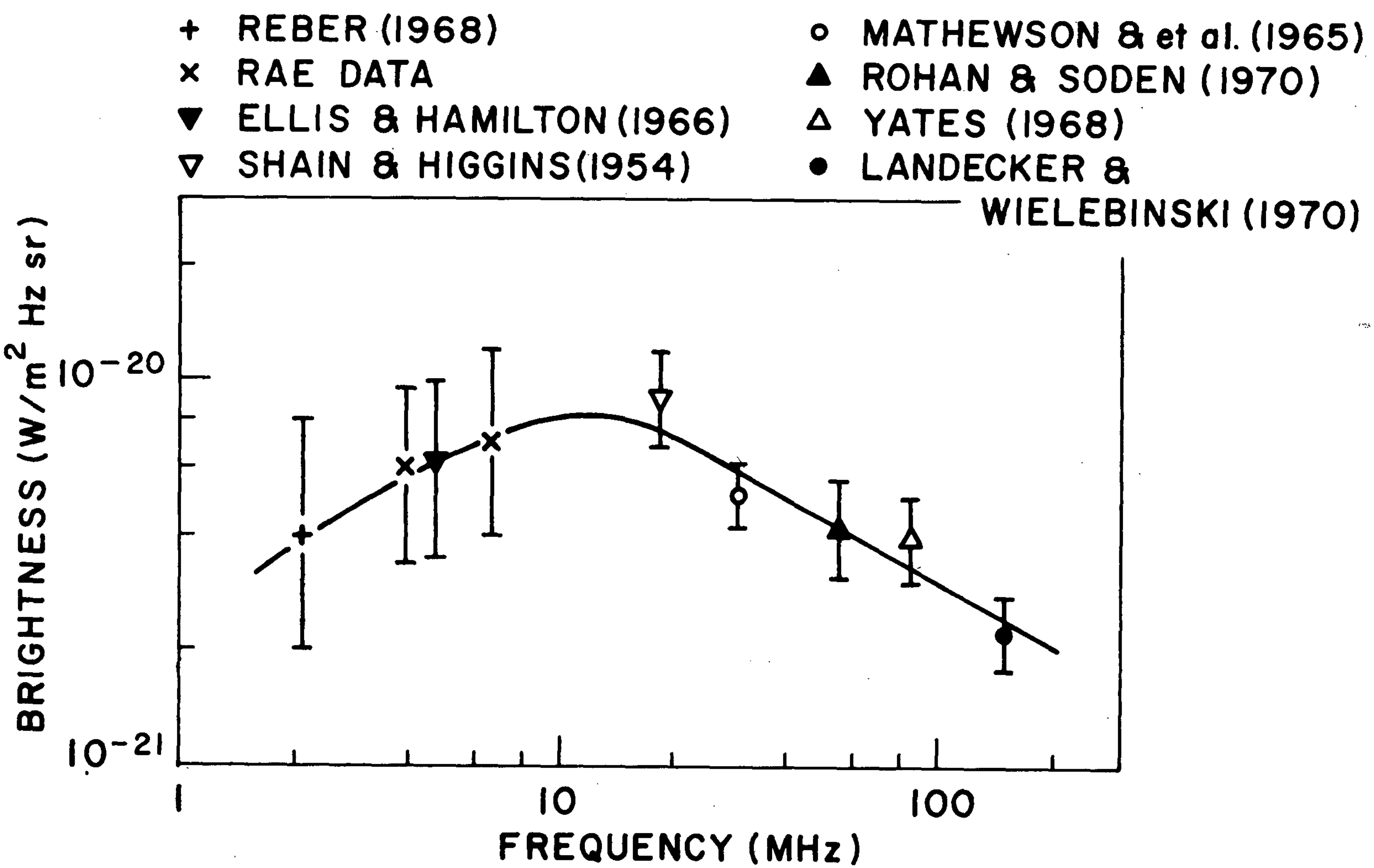

Figure 1. Radio spectrum of the region of the Gum Nebula.

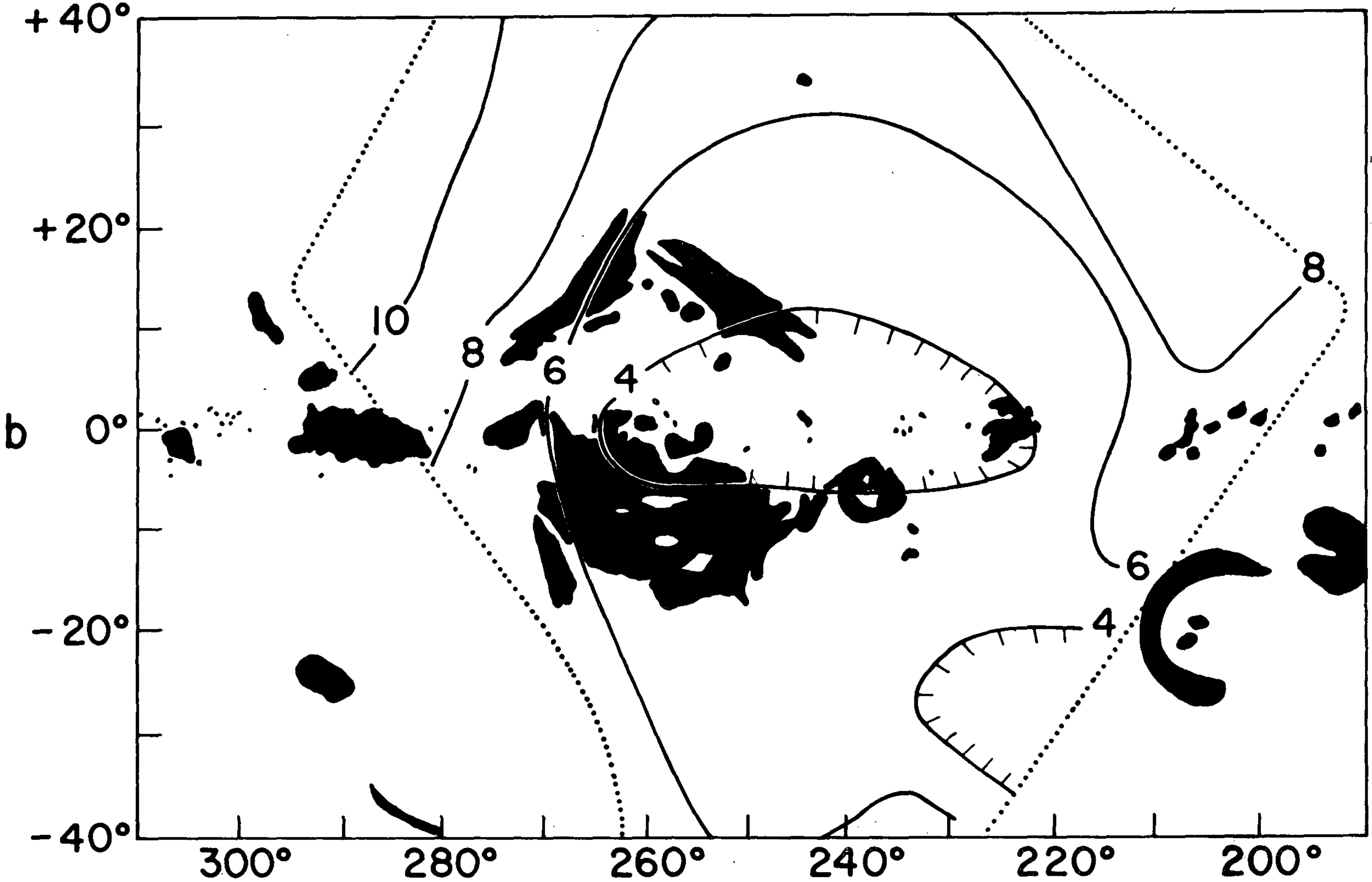

Figure 2. Preliminary map of the Gum Nebula region at 3.93 MHz from the RAE-1 satellite. The area enclosed by the dotted boundaries denotes the region for which there are satellite data for two separate surveys with orthogonal antenna beam orientations. The contours show isophotes of relative antenna temperature; one unit corresponds to a brightness temperature $\sim 3 \times 10^5$ °K.

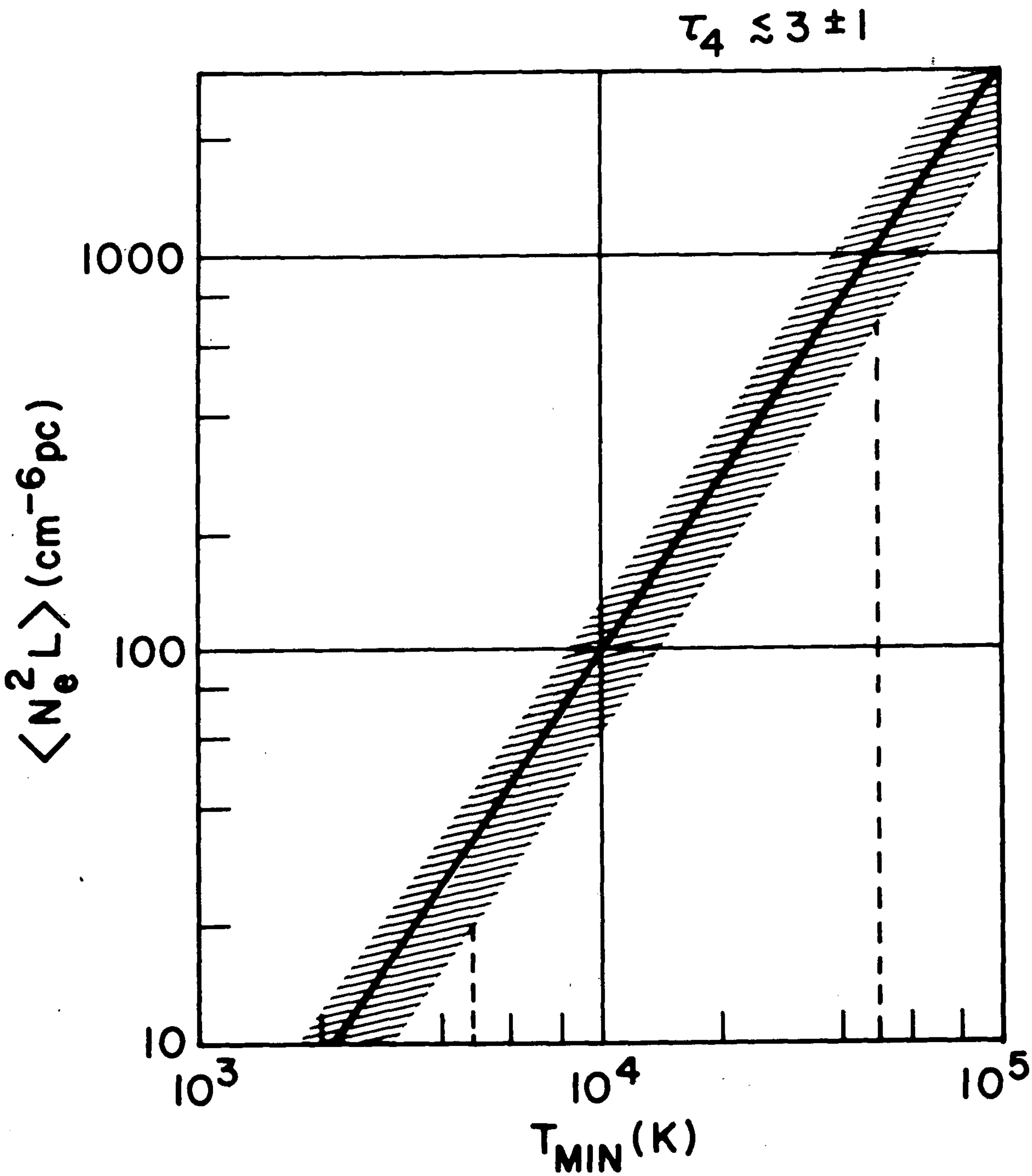

Figure 3. Plot of the average temperature of the Gum Nebula as a function of emission measure for $\tau_4 = 3$. The shaded area denotes the uncertainty in T_e corresponding to an uncertainty in τ_4 of ± 1.