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A MODEL OF THE LOCAL REGION OF THE GALAXY

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ABSTRACT

A two-component model of the local interstellar medium was developed, based on the Radio Astronomy Explorer (RAE-1) satellite observations of the low frequency (0.2 - 10 MHz) galactic radio background spectrum. The best fitting parameters support the two-component model of Hjellming et al. (1969), that is, cloud temperatures of 100K, intercloud temperatures of 1500K toward the anticenter direction and 2500K toward the north galactic pole direction, and a cloud filling factor of less than 1% The model shows evidence for a thick spiral arm and a thick electron disk of 600 and 1200 pc slab thicknesses, respectively. The temperature difference between the north galactic pole and anticenter directions supports the concept of a local positive thermal gradient away from the galactic plane. A preliminary discussion of the influence of the Razin effect on the model is also presented.

Key words: interstellar medium - galactic spectrum - two-component model

I. INTRODUCTION

The first suggestion that the interstellar medium might contain cold clouds and a hot intercloud medium came from B.G. Clark (1965). He proposed that the clouds are seen in absorption at 21 cm and have temperatures less than 100K, while the hot tenuous medium surrounding the clouds and seen in emission has a temperature around 1000K.

To explain the coexistence of the hot intercloud medium and the cold clouds, Hjellming, Gordon, and Gordon (1969, hereinafter referred to as HGG) suggested that the clouds are in pressure equilibrium with the intercloud medium. Independently, Field, Goldsmith, and Habing (1969, hereinafter referred to as FGH) produced a two-component model of the interstellar medium based on thermal instabilities. Their model had electron densities comparable to those of HGG but intercloud temperatures about a factor of ten higher. Several attempts have been made to distinguish between these two-component models. However, neither Hobbs and Zuckerman (1972), using interstellar sodium lines, nor Cesarsky and Cesarsky (1971), using hydrogen radio recombination lines, were able to choose between the models.

This paper is an attempt to fit the observed low frequency galactic background radio spectrum using a two-component model of the interstellar medium. At low frequencies, thermal free-free absorption dominates the spectrum. Because the thermal absorption process is sensitive to the electron density and temperature, the components of the interstellar medium can be studied through their absorption properties.

II OBSERVATIONAL DATA

The observational data to which the calculations were compared were obtained by the Radio Astronomy Explorer (RAE-1) satellite. For this study data from the dipole antenna were used. The receivers have a combined range of approximately 0.5 - 10 MHz in a total of 15 steps. Spectra of the low frequency continuum radiation from the north galactic pole (NGP), the anticenter (AC), and the galactic center (GC) directions were constructed using data taken during different times in the orbit when the dipole beam was centered on these directions in the sky. The probable error of the absolute value of the brightness for any one spectrum is $\pm 25\%$. A detailed description of the operation of the satellite and a complete analysis of the instrumental uncertainties are given by Weber et al. (1971). Preliminary results from the later Goddard Space Flight Center radio astronomy experiment on board the Interplanetary Monitoring Probe (IMP-6) satellite confirm the general shape of the RAE spectra (Brown and Alexander, 1971).

Alexander, Brown, Clark, and Stone (1970, hereinafter referred to as ABCS) published the spectra observed by RAE. They smoothed ground observations from 10-100 MHz with a dipole beam pattern and then combined them with the RAE data to produce the spectra, which were separated by Clark et al. (1970) into galactic and extragalactic components. The separation was performed assuming the spectrum could be represented by an analytic function. They used a multiparameter least squares fit to a function in which they assumed free-free absorption and power law emission spectra with spectral indices which were constant over the frequency range 0.5 - 100 MHz. The galactic disk spectral index was determined by the fact that the gas is optically thick at the lowest frequencies. Clark et al.'s galactic components of the NGP and AC spectra were used as standards in deriving our model. Our model is clearly dependent on the validity of their assumptions.

III. MODEL AND PROGRAM

Our model of the local region of the Galaxy assumed a two-component interstellar medium, with no physical relationships between the two components. The emission was assumed to be synchrotron radiation from cosmic ray electrons, with free-free absorption by thermal electrons.

We used a two-dimensional representation of the Galaxy, the plane being perpendicular to the galactic plane and passing through the galactic center and anticenter. A schematic cross-section of the initial geometry of the three spiral arms in the solar neighborhood is shown in Figure 1. The spiral arms were assumed to consist of two components, a warm intercloud region and randomly distributed cold denser clouds. The interarm region was assumed to consist of one component, having the same thermal electron density as the intercloud region, but a different synchrotron emissivity and thermal electron temperature. The distances to the neighboring spiral arms in the plane of the Galaxy are highly uncertain, and the actual numbers are merely best guesses; however, the order of magnitude is certainly correct. The distances in the z direction were chosen as reasonable initial values.

Analyses of pulsar dispersion measures and of low frequency absorption of extragalactic sources (Bridle and Venugopal, 1969) suggest that the equivalent thickness of the electron disk is greater than that of the hydrogen disk. In our model the interarm region was assumed to extend throughout the electron disk.

The spiral arm volume emissivity of the synchrotron radiation at 1 MHz was taken from ABCS, and their value of 0.4 for the synchrotron emission spectral index was also used. They measured the all-sky average brightness at 1 MHz to be 6×10^{-21} W m^{-2} Hz^{-1} sr^{-1}; taking an average optical depth of 2 for an average path length in the plane of 200 pc, they calculated the spiral arm volume emissivity in the local region to be 1×10^{-39} W m^{-3} Hz^{-1} sr^{-1}. Our model is clearly limited by the accuracy of ABCS's value for the local emissivity. It should be strongly emphasized that this emissivity applies only to the local region of our spiral arm.

Based on these assumptions, a computer program was written to calculate an expected spectrum. The calculations were done by integrating the equation of transfer at each frequency along each line of sight in a radial grid centered on the sun. For each distance increment the program used the parameters appropriate to the region in which this step occurred. Lines of sight were separated by 5°, and averaging of the brightness contribution from each line of sight was done over a 100° fan-shaped beam which approximates a dipole pattern.

The calculated spectrum was compared to the appropriate (NGP or AC) standard spectrum. A fit was considered "good" if the shape of the calculated spectrum was similar to that of RAE and if all the calculated points lay within the RAE error limits.

IV. DISCUSSION AND RESULTS

The synchrotron volume emissivity at 1 MHz for the spiral arms (both cloud and intercloud regions) was fixed at 1.0×10^{-39} W m^{-3} Hz^{-1} sr^{-1}. From fitting the high frequency part of the spectrum where the thermal gas is essentially transparent, the interarm emissivity was found to be 0.16×10^{-39} W m^{-3} Hz^{-1} sr^{-1}. This gave an arm/interarm ratio of 6 to 1 and an average emissivity over a typical path through both arm and interarm regions of 0.4×10^{-39} W m^{-3} Hz^{-1} sr^{-1}. Measurements of the synchrotron volume emissivity have been made by Bridle (1968) and Purton (1966) at 10 MHz, Andrew (1969) at 13 MHz, and Roger (1969) at 22 MHz. Scaling their results to 1 MHz with a spectral index of 0.4 gives an average of 0.3×10^{-39} W m^{-3} Hz^{-1} sr^{-1}, which agrees well with the average value determined from the model.

It should be noted that at frequencies above 10 MHz the observed synchrotron emissivity is a poorly known type of average over arm and interarm regions. In an attempt to avoid any controversy over the value for the local emissivity obtained by ABCS, the extrapolated value of 0.3×10^{-39} W m^{-3} Hz^{-1} sr^{-1} was tried as a uniform emissivity throughout both arm and interarm regions. While a good fit was obtained at the low frequency end of the spectrum by resorting to an intercloud temperature of 6000K toward the NGP and 4000K toward the AC, a good fit at the high frequency end was not possible in this case without raising the interarm emissivity above that of the spiral arms. This would be contrary to the current belief (Baldwin, 1967) that the emissivity is higher in the arms, where the magnetic field is compressed. Recent results from the Westerbork continuum survey of M51 at 1415 MHz show that in that galaxy the emissivity in the radio arm is significantly greater than that between the arms (Mathewson et al., 1972).

One of the most sensitive parameters in the model is the intercloud thermal electron temperature. Changes in the intercloud temperature directly affected the low frequency end of the spectrum (< 2 MHz). The temperature was varied between 500 and 10000K while keeping the thermal electron density constant. Figure 2 is a comparison of model spectra for various intercloud temperatures with the observed RAE galactic spectrum. The best fit was obtained with a temperature of about 2500K for the NGP and 1500K for the AC. This supports the concept of a positive thermal gradient away from the galactic plane (Bridle and Venugopal, 1969). Because the low frequency end of the spectrum is formed within the first few hundred parsecs of the sun, the thermal gradient occurs within our spiral arm, and is thus a local phenomenon. The two temperatures are in agreement with those favored by HGG.

The clouds affected the spectrum only near the turnover, indicating that the low frequency end of the spectrum arises primarily from intercloud regions closer to the sun than the nearer clouds. Equally good fits were obtained for cloud temperatures greater than 50K. A reasonable value of 100K was chosen.

The interarm thermal electron temperature was varied between 500 and 10000K. However, the optimum value is not well defined as the temperature only slightly influenced the region of the spectrum between 1 and 10 MHz. At these frequencies the thermal gas is nearly transparent and only a lower limit of 3000K for the NGP and 2500K for the AC can be set.

Various theories and observations of the interstellar medium quote electron density values which are approximately similar, while the published temperature values vary much more widely. For this reason, representative values of the electron densities, based on theory and direct observations, were chosen and kept fixed for all the models. We used 0.028 cm^{-3} for the intercloud and interarm regions and 0.044 cm^{-3} for the clouds. These values were taken from HGG's interpretation of observations of the Crab nebula pulsar, and are representative of the work of other authors.

Realizing the limitations of fixing the densities, we tried values a factor of two less than the densities listed above. These are very close to those favored by FGH. However, in order to have the same amount of free-free absorption with these densities, the temperature must be decreased rather than increased. Therefore, to build this model around the high temperatures advocated by FGH, some means of reducing the emission other than free-free absorption must be involved.

The linear filling factor is defined as the path length through clouds divided by the path length through the intercloud region. A linear filling factor of less than 1% (that is, 100 pc of intercloud region along the line of sight for every 1 pc of clouds) was found to give the best fitting spectrum. For the line of sight to the Crab nebula pulsar, HGG found 18 pc of clouds over their total path of 2020 pc, giving a linear filling factor of about 1%.

In order to fit the high frequency end of the spectrum (50 - 100 MHz) in the NGP direction, it was necessary to increase the original spiral arm and electron disk dimensions to 300 and 600 pc. Alternatively, keeping the spiral arm semi-thickness at 150 pc it was necessary to inflate the electron disk to a slab semi-thickness of 1225 pc. These two cases are indistinguishable because in the model path length and emissivity are inseparable. A thick electron disk is consistent with the conclusions of Bridle and Venugopal (1969) and Silk (1971) that the equivalent thickness of the electron disk is much greater than that of the neutral hydrogen disk.

Figures 3(a) and 3(b) show the best fits between the model and the disk component of the RAE spectrum for both the NGP and AC. The error bars shown are representative of the errors for the RAE spectra, $\pm 25\%$ probable error in absolute brightness. The parameters used to calculate these spectra are summarized in Table 1.

During the course of this research, Stephens (1971) published results of a similar investigation. Using his parameters in our model, it was confirmed that his calculated spectrum also fits the observed RAE spectrum. Contrary to our model, the major portion of the emission in his model is provided by a halo component. While the question of the existence of the halo is not yet settled, the weight of the evidence appears to be against a large spherical halo (Ginzburg, 1970). Observations by Wielebinski and Peterson (1968), Price (1970), and Lequeux (1971), do not support the existence of a halo.

VI. RAZIN EFFECT

Ramaty (1972) has calculated the influence of the ionized interstellar medium on synchrotron emission. He found that at low frequencies the emission is moderately suppressed due to the Razin effect. For the densities used in our model, and for fields of about 3μG, the effect is not negligible at frequencies below 10 MHz. The emission spectra given in Ramaty's (1972) figure 2 for observation angles of 45° and 90° between the line of sight and the magnetic field lines were scaled to the gyro and plasma frequencies implied by our model. The spectra, extrapolated in a straight line from high frequencies, were normalized to an emissivity value of 1.0×10^{-39} W m^{-3} Hz^{-1} sr^{-1} at 1 MHz.

The effect of using these spectra for the emission was to raise the intercloud and interarm thermal electron temperatures by at least a factor of two. The values are summarized in Table 2. In the AC and NGP directions the average angle between any line of sight and the magnetic field lines over a dipole beam is probably between 45° and 90°. Therefore the intercloud temperatures in Table 2 for the two angles can be considered as upper and lower limits. The temperatures are still closer to the HGG model although they are beginning to approach those favored by FGH.

Figure 4 is a comparison of the model spectra, including the Razin effect, with a combination of IMP-6 (Brown, 1972) and RAE spectral measurements. The IMP-6 data have been included, since they are more reliable than the RAE data at the lower frequencies where the Razin effect is likely to dominate. The IMP-6 data fall off faster than the model spectra. This can be corrected by increasing both the thermal absorption and the Razin effect by slightly raising the intercloud thermal electron density.

VII SUMMARY AND CONCLUSIONS

Some of the limitations of the model should be reviewed. The assumptions used by Clark et al. (1970) to separate the galactic component of the observed RAE spectra are inherent in this model. The model is also heavily dependent on the accuracy of the value for the local emissivity derived by ABCS. The dipole beam along with the two-dimensional geometry impose the major structural limitations. The large beam smears out discrete absorption sources such as the cold clouds, obscuring the distinction between many weakly absorbing clouds and fewer nearly opaque clouds. In order to keep the model simple, the cloud and intercloud regions are each considered to be uniform.

The conclusions can be summarized as follows. The best fitting intercloud temperatures and cloud filling factor support the two-component model of HGG. With the Razin effect included, the temperatures are raised enough to begin to support the FGH model. There is evidence for a local thermal gradient with temperature increasing away from the plane of the Galaxy. There is also evidence for a spiral arm and electron disk which are inflated in the z direction. The arm/interarm emissivity ratio was found to be 6 to 1, and the average over long path lengths agrees with values scaled from higher frequency data.

Spectra are needed with higher angular resolution at these low frequencies. This would allow the cloud parameters to be better defined. and the variation of intercloud parameters within each region to be taken into account. More information is needed about the volume emissivities at low frequencies and better observations of the absorbing constituents.

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TABLE 1

A summary of the parameters for the best fitting spectra. The starred (*) quantities were assumed, the others were derived.

	Intercloud	Cloud	Interarm
Emissivity ($W\ m^{-3} Hz^{-1} sr^{-1}$)	1.0×10^{-39} *	1.0×10^{-39} *	0.16×10^{-39}
Temperature (K) NGP	2500	100	>3000
Temperature (K) AC	1500	100	>2500
Electron density (cm^{-3})	0.028 *	0.044 *	0.028 *
Filling factor		$<1\%$	

TABLE 2

A summary of the temperatures for the best fitting spectra including the Razin effect.

	$\theta = 90^\circ$		$\theta = 45^\circ$	
	Intercloud	Interarm	Intercloud	Interarm
Temperature (K) NGP	5000	>8000	8000	>8000
Temperature (K) AC	2500	>8000	3500	>5000

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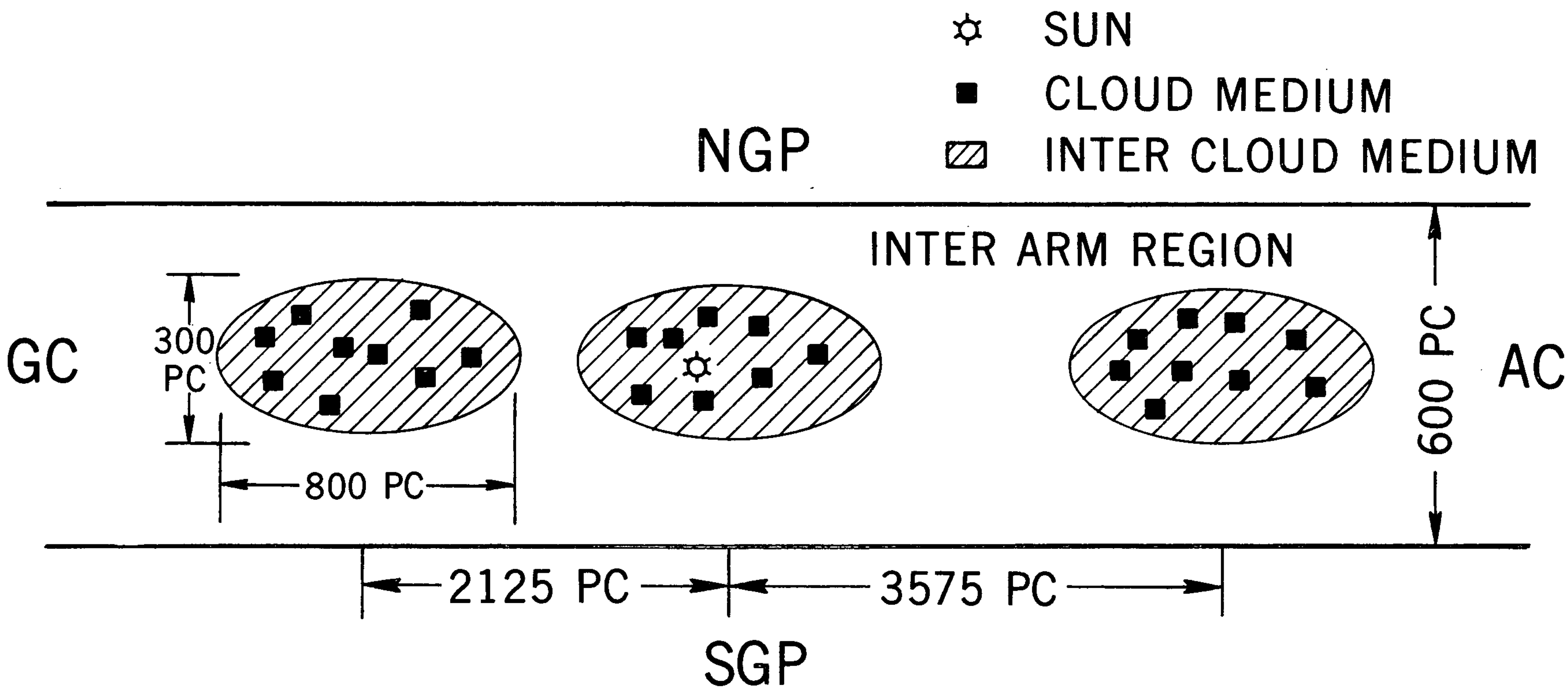
FIGURE CAPTIONS

Figure 1 - A schematic cross section of the initial geometry of the model. A cross section of the three spiral arms in the solar neighborhood is shown, with the sun imbedded in the middle arm. The distribution of clouds shown is typical of the random gaussian distribution used in the model.

Figure 2 - A comparison of model spectra for various inter-cloud temperatures with the disk component of the RAE spectrum. The cloud temperatures were fixed at 100K; the linear filling factor was 0.2%.

Figure 3 - A comparison of the model and the disk component of the RAE spectrum for (a) the north galactic pole and (b) the anticenter. The error bars shown are representative of the errors for the RAE spectra.

Figure 4 - A comparison of the model including the Razin effect with a combination of IMP-6 and RAE spectrum for (a) the North Galactic Pole and (b) the anticenter. The error bais are representation of the IMP-6 spectra. The model spectra are for an angle of 45^{o} between the line of sight and the magnetic field line.


SUN
CLOUD MEDIUM
INTER CLOUD MEDIUM
NGP
INTER ARM REGION
GC
300 PC
800 PC
600 PC
AC
2125 PC
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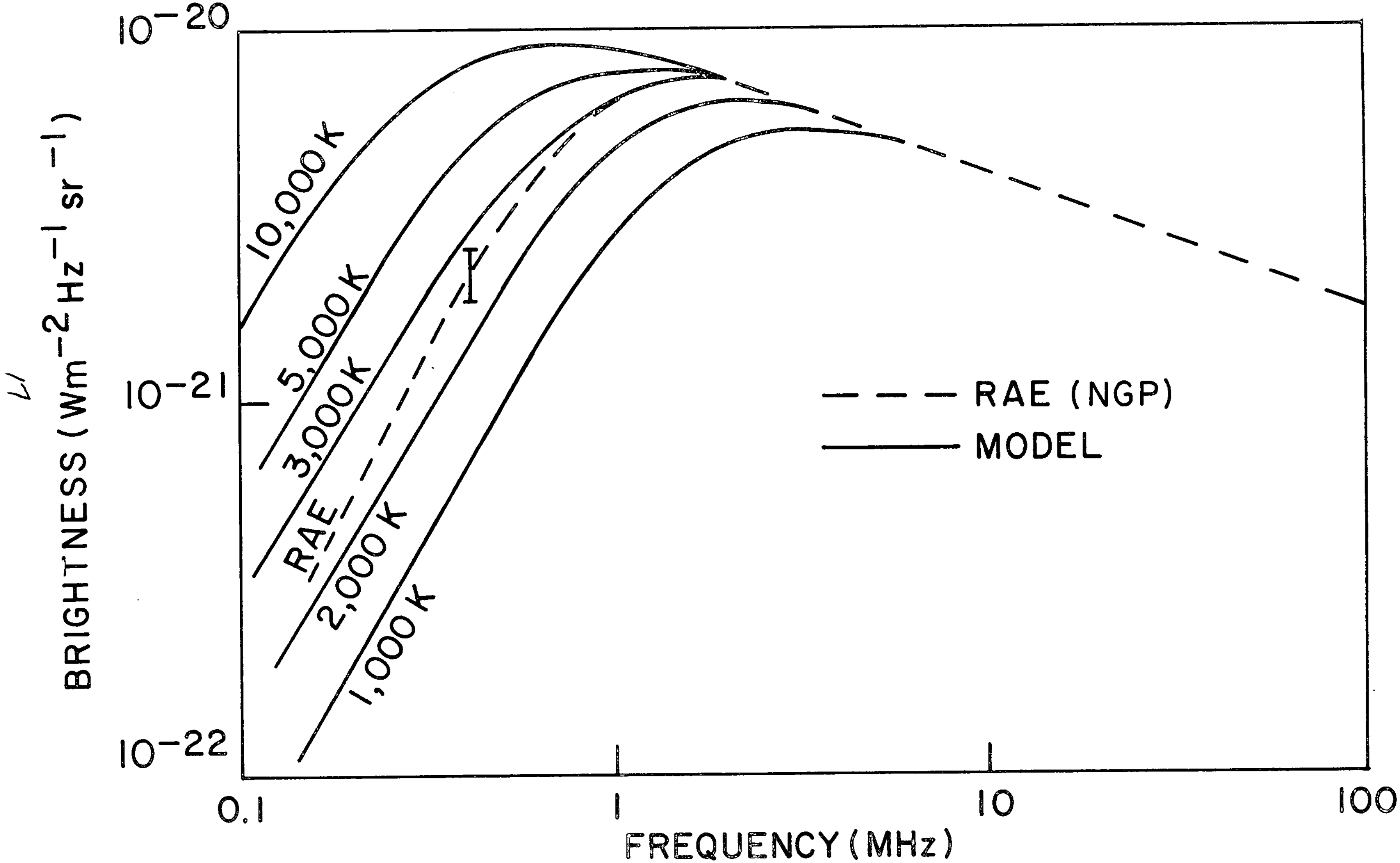
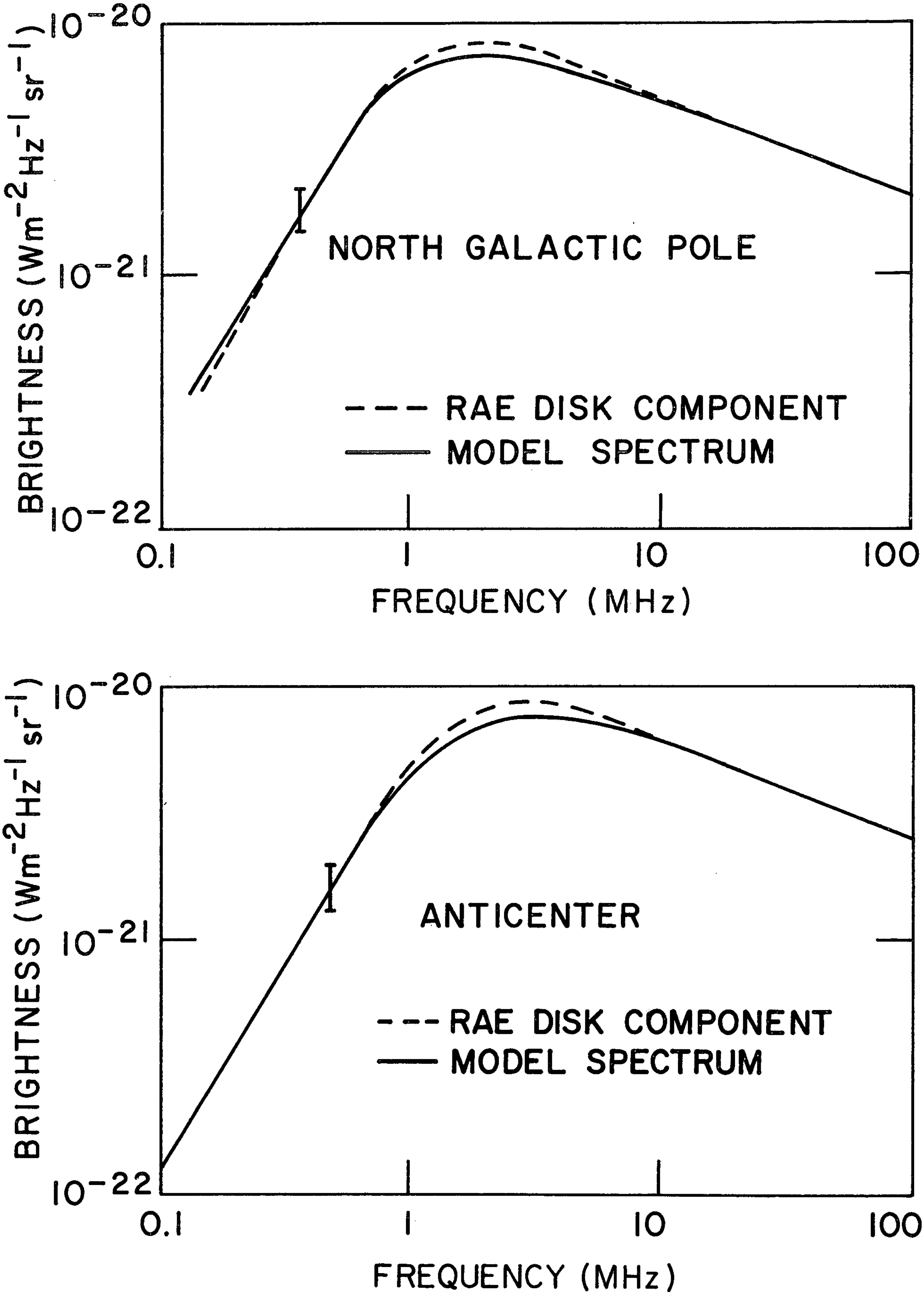
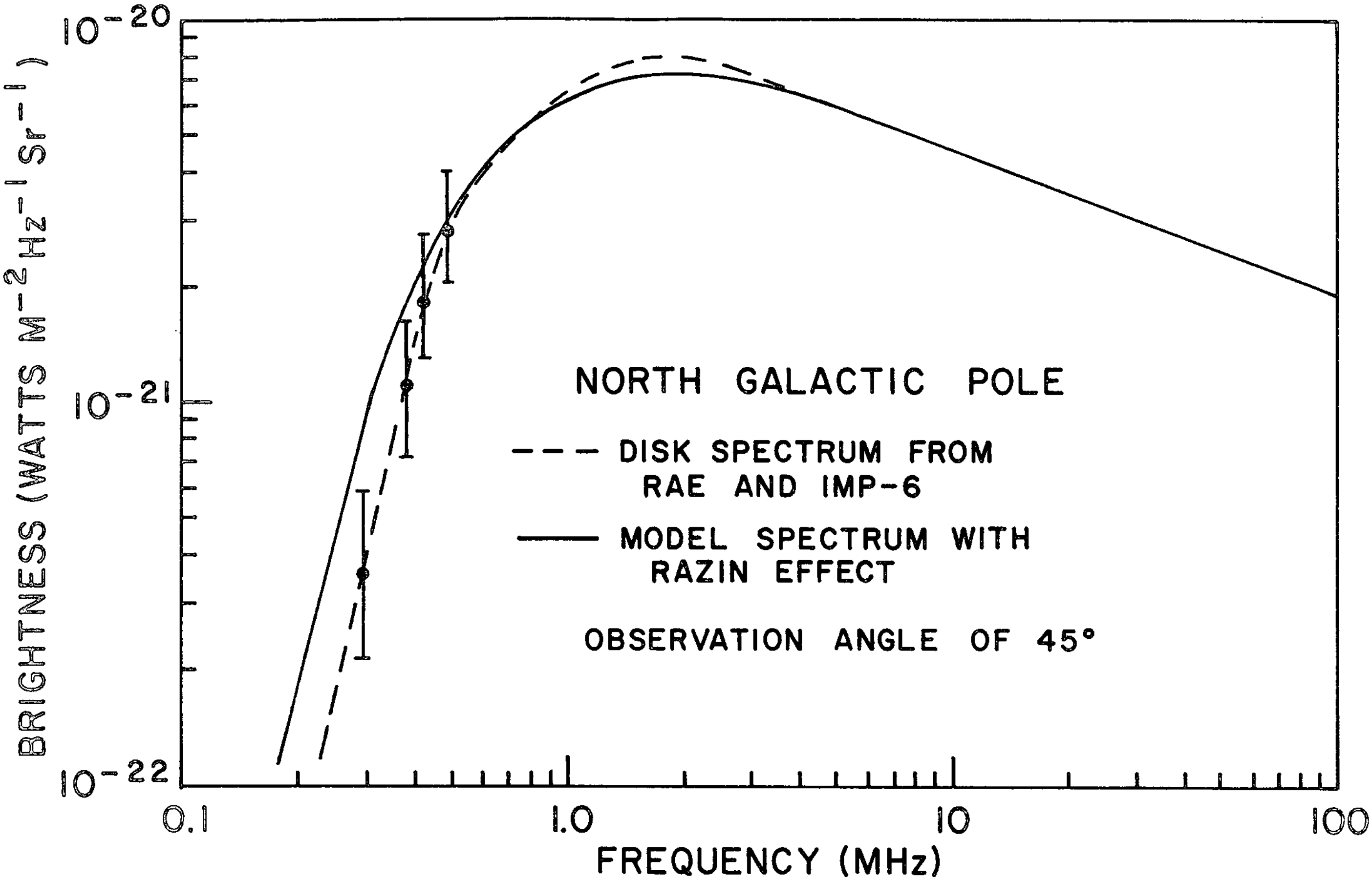
SGP

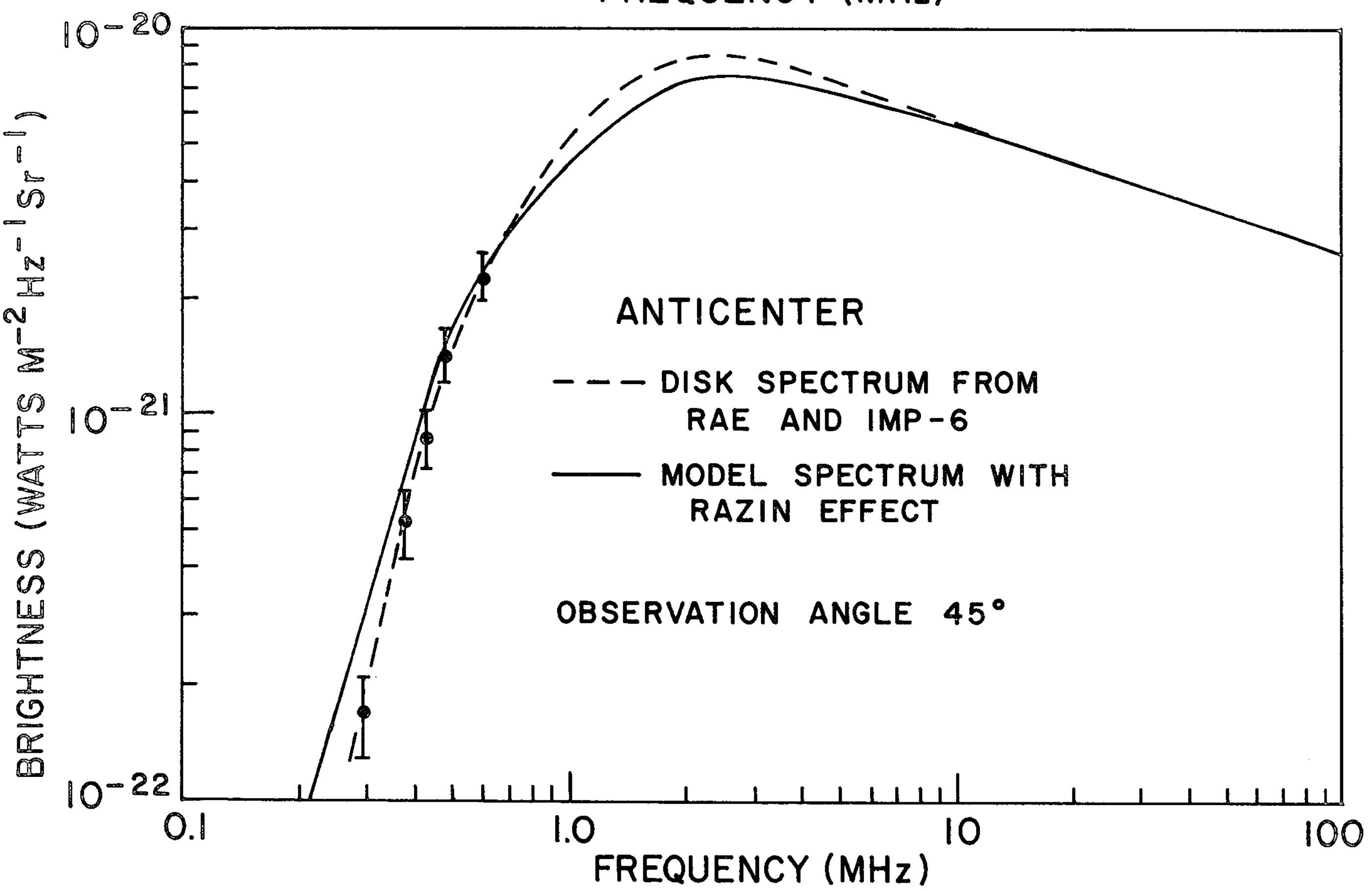


17
BRIGHTNESS (Wm⁻² Hz⁻¹ sr⁻¹)
10⁻²⁰
10⁻²¹
10⁻²²
10,000 K
5,000 K
3,000 K
RAE
2,000 K
1,000 K
RAE (NGP)
MODEL
0.1
1
10
100
FREQUENCY (MHz)



BRIGHTNESS (Wm⁻²Hz⁻¹sr⁻¹)
10⁻²⁰
10⁻²¹
10⁻²²
NORTH GALACTIC POLE
RAE DISK COMPONENT
MODEL SPECTRUM
0.1
1
10
100
FREQUENCY (MHz)
BRIGHTNESS (Wm⁻²Hz⁻¹sr⁻¹)
10⁻²⁰
10⁻²¹
10⁻²²
ANTICENTER
RAE DISK COMPONENT
MODEL SPECTRUM
0.1
1
10
100
FREQUENCY (MHz)


10^-20
10^-21
10^-22
BRIGHTNESS (WATTS M^-2 Hz^-1 Sr^-1)
NORTH GALACTIC POLE
DISK SPECTRUM FROM RAE AND IMP-6
MODEL SPECTRUM WITH RAZIN EFFECT
OBSERVATION ANGLE OF 45°
0.1
1.0
10
100
FREQUENCY (MHz)


10^-20
10^-21
10^-22
BRIGHTNESS (WATTS M^-2 Hz^-1 Sr^-1)
ANTICENTER
DISK SPECTRUM FROM RAE AND IMP-6
MODEL SPECTRUM WITH RAZIN EFFECT
OBSERVATION ANGLE 45°
0.1
1.0
10
100
FREQUENCY (MHz)