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The Galactic background radiation from 0.2 to 13.8 MHz

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Abstract. The radio frequency receivers of the WAVES instrument on the WIND spacecraft are used to determine the direction of maximum intensity of the Galactic noise background in the frequency range 0.2 to 13.8 MHz. The observations are made with dipole antennas spinning in the ecliptic plane, hence provide information on the large scale distribution of intensity. The main results are: (1) the direction of maximum brightness at the higher frequencies is close to that of the Galactic center, (2) in an intermediate range around 3–4 MHz the brightness appears isotropic, and (3) at frequencies of 3 MHz and lower the maximum brightness is at the ecliptic longitude nearest the Galactic poles. On the basis of previous observations these results are not unexpected, but this is the first time that a precise spectrum has been made over this large frequency range.

Key words. Galaxy: general – radio continuum: general; ISM – ISM: general

1. Introduction

The Galactic background radiation has been studied for decades and maps of part or all of the sky have been produced at many frequencies. Concentrating on those at $f <$ 50 MHz, there are maps by Maeda et al. (1999, 45 MHz, $+5° < \delta < +65°$), Dwarakanath & Udaya Shankar (1990, 34.5 MHz, $-50° < \delta < +70°$), Cane (1978, 30 MHz, all sky), Roger et al. (1999, 22 MHz, $-28° < \delta < +80°$), Cane (1977, 10 MHz, $-90° < \delta < +20°$), Bridle (1967, 13 and 17.5 MHz, $+16° < \delta < +70°$), and Ellis (1982, see below). At all frequencies greater than of order 10 MHz the brightness is higher along the Galactic equator than near the Galactic poles, and the peak brightness is located in the direction of the Galactic center. However, at a frequency of about 5 MHz the contrast between Galactic equator and Galactic poles disappears, and at yet lower frequencies the regions in the vicinity of the Galactic poles are brighter than the equator, and in particular, there is a minimum of brightness in the direction of the Galactic center.

Ellis (1982) presents a remarkable series of maps of the brightness distribution at low Galactic longitudes from north of the Galactic center to near the south Galactic pole (SGP). The maps are at 7 frequencies between 2.1 and 16.5 MHz, with angular resolution varying between 7.5° at 2.1 MHz to 1.5° at 16.5 MHz. For example, at 2.1 MHz he finds that the region near the SGP is about 10 times brighter than the Galactic center, at 4.7 MHz the two brightnesses are about equal, and at 16.5 MHz the Galactic center is 3–4 times brighter than the SGP.

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The above observations were made with ground-based telescopes. In space, techniques are not yet available to make maps with comparable angular resolution. Present observations of the Galactic background radiation at frequencies observable only from space have been with short dipoles whose beam solid angles are $\Omega_{\rm beam} = 8\pi/3$ sr (e.g. Brown 1973), or with the RAE satellites whose V-type antennas had resolution $\Omega_{\rm beam}$ varying from ≈1 sr at 10 MHz to ≈8 sr at 0.25 MHz (Alexander et al. 1975).

A summary of ground and space observations of the spectrum of the radiation from the SGP was given by Cane (1979), who derived an empirical formula to describe the spectrum from 1 to 100 MHz. More recent measurements of the spectrum below a few MHz were summarized by Dulk et al. (2001), together with a new, preliminary spectrum from 0.15 to 0.4 MHz derived from Wind spacecraft observations. Below 0.15 MHz the spectrum is very uncertain because the quasi-thermal plasma noise from the vicinity of the spacecraft becomes the dominant noise source and masks the radiation from the Galaxy.

Brown (1973) measured the spectrum of the Galactic background radiation from 0.13 to 2.6 MHz using the spinning dipole antenna of the IMP-6 spacecraft. The intensity was modulated at twice the spin frequency of the spacecraft, with the modulation decreasing from about 35% at 0.13 MHz to 6% at 2.6 MHz. From the phase of the modulation he found that, at all frequencies, the brightest radiation arrived from the direction of the Galactic poles, not the Galactic center.

Novaco & Brown (1978) presented maps of most of the sky made with the RAE2 spacecraft at 6 frequencies between 1.3 and 9.2 MHz. In the maps at frequencies 4.7 MHz and higher the brightness is generally highest near the Galactic equator; the minimum brightness is near the SGP, but more precisely near Galactic longitude 220°, latitude −40°. At frequencies 3.9 to 1.3 MHz, the brightness distribution tends to be more or less isotropic. However, in view of the measurements of Brown (1973) and Ellis (1982), it is surprising that the maps at all frequencies show a higher brightness at the Galactic equator than at the Galactic poles.

In this paper we utilize the unprecedented frequency coverage of the WAVES experiment on the Wind spacecraft to observe how the spin-induced modulation varies with frequency and to determine the direction of arrival of the brightest radiation.

2. Instrument

The WAVES experiment on the Wind spacecraft (Bougeret et al. 1995) observes at hundreds of frequencies lower than 13.8 MHz. The Wind spacecraft is in a complex orbit in the Sun-Earth system that places it far from Earth for the large majority of the time. It is spin stabilized with the spin axis perpendicular to the ecliptic plane.

The WAVES antennas used here are long wires located in the spin plane of the spacecraft, the ecliptic plane. The spacecraft rotates with a 3 s period. The "X antenna", 2×50 m long, is used for frequencies up to 1 MHz, and the "Y antenna", 2×7.5 m long at an angle of 90° from the X antenna, is used for frequencies between 1 and 13.8 MHz.

The received intensity of the Galactic background radiation is proportional to the convolution of the Galactic brightness distribution with the response pattern of the dipole antennas, which are short dipoles over much of their frequency range. As the antennas rotate, the received intensity varies from a maximum approximately when the antenna is broadside to the regions of highest brightness, to a minimum when it is broadside to the regions of lowest brightness (e.g. Manning & Fainberg 1980). Thus in each half rotation of the spacecraft, or 1.5 s, there is an approximately sinusoidal intensity variation whose amplitude is a measure of the minimum to maximum brightness within the dipolar response pattern, and whose phase determines the direction of maximum and minimum brightness.

3. Results

The observations were made on 6 May 1997 when the Wind spacecraft was near the L1 point, 210 $R_\oplus$ from Earth. The data were averaged over a period of about 8 hours when solar activity was very low; only one solar burst occurred and it was excised from the data. In addition, the Earth's auroral kilometric radiation, which often occupies the range 0.1–0.4 MHz, was also unusually low. Most importantly, the plasma density in the vicinity of the Wind spacecraft was unusually low $n_{\rm e} \approx 4.5\,{\rm cm}^{-3}$ (plasma frequency $f_{\rm p} \approx 19$ kHz); a low plasma density is essential so that the quasi-thermal plasma noise is negligible in the frequency range of interest, above 0.2 MHz.

Figure 1 shows the spectrum of the Galactic background radiation from 0.2 to 13.8 MHz: Previous measurements of brightness temperature (top panel), our measurements of degree of spin modulation of the signal from the Galaxy (middle panel) and of the spin phase of maximum brightness (bottom panel).

In the top panel, the solid line at frequencies higher than 1 MHz was derived by Cane (1979), who synthesized a large number of ground and space observations by about 20 observers. The spectrum was made for the direction of the south Galactic pole (SGP), but it applies to large regions near both Galactic poles. The dashed line, which diverges from the solid line at $f > 3$ MHz, is the correction derived by Dulk et al. (2001) for the enhanced emission of the Galactic equator as viewed by a low-gain (dipole) antenna. The dot-dashed line from 0.4 to 1 MHz is an extrapolation of Cane's (1979) spectrum using her formulas. The dotted line extension from 0.2 to 0.4 MHz is the preliminary measurement from the Wind spacecraft reported by Dulk et al. (2001); it agrees with independent measurements by observers of other spacecraft to within a factor of about two.

The figure shows that $T_{\rm B}$ is approximately constant at $T_{\rm B} \approx 1.5 \times 10^5$ K below 1–2 MHz, and decreases rapidly above ∼3 MHz. These features are explained by the optical thickness τ_ν which, according to Cane (1979), goes as $\tau_\nu = 5\nu^{-\beta}$ with $\beta = 2.1$, so that $\tau_\nu = 1$ at 2.1 MHz. However, at 0.2 MHz the brightness temperature measured by Wind is about a factor of two smaller than that predicted by an extrapolation of Cane's formulae; this difference can be accounted for if $\beta > 2.1$ in the formula for τ_ν at $f \lesssim 0.5$ MHz.

The two lower panels show the present observations of spin modulation and phase as taken by the WAVES instrument on 6 May 1997. Data from both the X and Y antennas is included, with correction for the orthogonal directions of the two antennas. A Fourier analysis was used to find the degree and phase of spin modulation.

The major feature of the spectrum of degree of spin modulation is the well defined minimum of essentially zero modulation at 3.6 MHz. At frequencies higher than 3.6 MHz it rises to about 12% at 13.8 MHz. At frequencies lower than 3.6 MHz it rises to a plateau of 20% from 0.4 to 0.8 MHz and then rises further to about 27% at 0.2 MHz.

The minimum degree of modulation occurs at the frequency, 3.6 MHz, where the brightness temperature of the Galactic background radiation approaches saturation (according to Cane's (1979) formula, $\tau_\nu(3.6\ {\rm MHz}) = 0.34$). In terms of specific intensity, $I_\nu = k\,T_{\rm B}/\lambda^2$, this is where I_ν attains its maximum value of 2×10^{-20} W m^{-2} Hz^{-1} sr^{-1}.

In the lower panel of Fig. 1, the phase of maximum brightness is given in ecliptic longitude, $l_{\rm ecl}$, where 0° is the direction of the Vernal Equinox. (It is also the direction of the Autumnal Equinox due to the 180° ambiguity inherent in observations with a dipole antenna.)

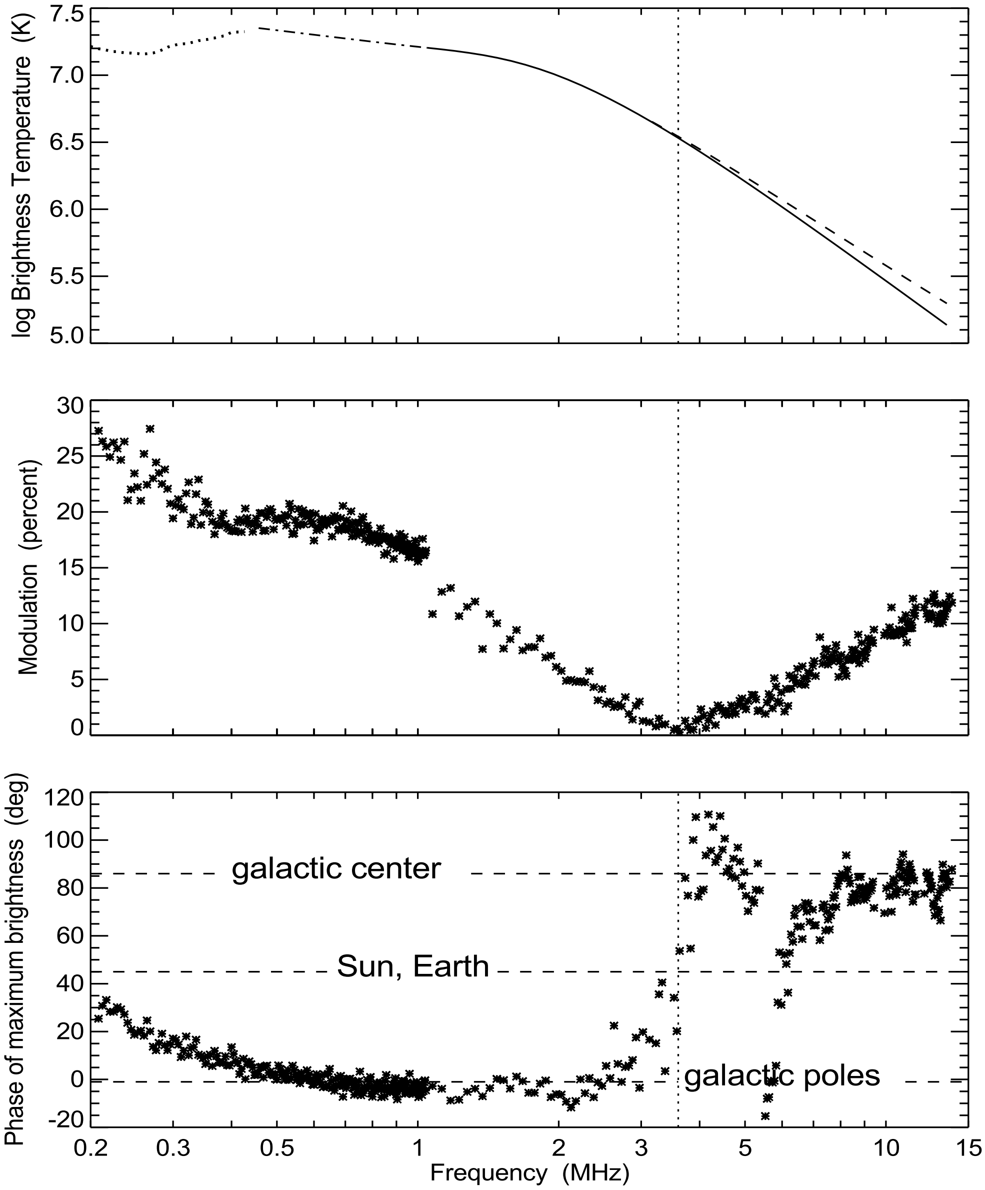

Fig. 1. Top panel: Estimated spectrum of brightness temperature of the Galactic background radiation obtained from sources described in the text. Middle panel: Wind/WAVES measurements of the degree of modulation (peak minus average power) of the signal from the Galactic background. The meaurement uncertainty is evident from the variation from one frequency to another. Bottom panel: Spin phase of maximum intensity. The ordinate is ecliptic longitude, with an ambiguity of 180° inherent in reception by a dipole antenna.

In ecliptic coordinates, the Galactic center is only 5° south of the ecliptic at $l_{\rm ecl} = 266°$ (or 86° with the 180° ambiguity). The Galactic poles are about 30° north and south of the ecliptic at $l_{\rm ecl} = 0°$ and 180°. The Sun and Earth were at $l_{\rm ecl} = 45°$ and 225° on the day of observations. These longitudes are marked in Fig. 1.

The major feature of the phase of maximum intensity is the rapid shift from $l_{\rm ecl} = 80$–$85°$ at $\gtrsim 4$ MHz to near 0° at 0.5–3 MHz, and the slow rise to $\sim$30° at 0.2 MHz. Between 3 and 4 MHz the phase is poorly determined because the modulation is so nearly zero. Between 5 and 6 MHz there is an anomaly which we believe is an instrumental artifact due to the mutual coupling of the Y antenna at the resonance frequency of the magnetometer boom that is located 45° from the antenna.

Clearly, at $f \gtrsim 4$ MHz the ecliptic longitude of maximum intensity, as convolved with the antenna pattern of a short dipole, is very close to the Galactic center/anticenter, within about 5°. Between 0.4 and 3 MHz the maximum intensity is near the ecliptic longitude closest to the Galactic poles. The Sun and Earth appear not to influence the phase of maximum intensity, as expected.

The observational result below $\sim$0.4 MHz is puzzling: The phase of maximum brightness curves upward to about $l_{\rm ecl} = 30°$ (or 210°) and the degree of modulation rises to $\sim$27°. We are not aware of what Galactic feature or features cause this shift. It is unlikely that the quasi-thermal plasma noise affected the signal at $\gtrsim 0.2$ MHz because the plasma frequency was < 0.02 MHz when the observations were made.

4. Discussion and conclusion

Given the previous observations described in the introduction our results represent a confirmation of some of them and an extension to a wider and more detailed spectrum. We are generally in accord with the results of Brown (1973) who observed in the range 0.2 to 2.6 MHz, and with the 2.1 MHz map of Ellis (1982): The modulation decreases with frequency and the brightest areas of the sky are at ecliptic longitudes closest to the direction of the Galactic poles. At frequencies $\gtrsim 4$ MHz our results are in accord with the known result that the brightest area of the sky is in the direction of the Galactic center (e.g. maps at 16.5 MHz of Ellis 1982 and at 10 and 30 MHz by Cane 1977, 1978).

Our spectrum shows for the first time the details of how the spin modulation drops to zero at 3.6 MHz and the spin phase of maximum intensity shifts abruptly by about 90°. At 3.6 MHz the sky is fully isotropic, at least as observed with a dipole antenna spinning in the ecliptic plane.

Combining these and previous observations we arrive at a general picture of how the appearance of the Galactic background radiation changes with decreasing frequency. At $\gtrsim 100$ MHz the optical depth τ_ν is less than unity in all directions, and the Galactic equator is highly structured with a maximum toward the Galactic center that is much brighter than the poles. Near 100 MHz, τ_ν in the direction of the Galactic center is near unity as evidenced by the fact that the Galactic center itself, Sgr A, is not observed at 80 MHz (Dulk 1970).

Proceeding to lower frequencies, the regions where τ_ν is greater than unity extend to more and more of the Galactic equator, reducing the contrast between it and the Galactic poles. Then, below about 10 MHz, regions of the Galaxy away from the Galactic plane become optically thick, and at $\approx$3.6 MHz, τ_ν is nearly unity in all directions, so the radiation appears isotropic.

At even lower frequencies the surface of unity optical depth approaches closer and closer to the solar system, but less rapidly in the direction of the poles than toward the toward the Galactic equator because much of the absorbing material is concentrated in the Galactic plane.

Regarding the question: Why are the Galactic poles brighter than the equator? Part of the answer may be that the synchrotron radiation from relativistic electrons can reach us from larger distances in the direction of the poles than in the Galactic equator. It is generally accepted that the large optical depth at $f \lesssim 3$ MHz is due to absorption by electrons of the Warm Ionized Medium (e.g. review by Dwarakanath 2000). On the other hand, the emissivity of the synchrotron radiation depends on the interstellar magnetic field strength, field direction, and the energy distribution function of the relativistic electrons. Near the $\tau_\nu = 1$ surface in the polar direction the magnetic field strength, direction and the relativistic electron energy distribution may be different from those near the $\tau_\nu = 1$ surface in the Galactic plane, and the path length is longer. It is not clear which one of these factors is the most important, but the result is that the brightness is larger in the polar direction.

While this scenario may account in general for the observations to date, it is overly simple in not taking into account the irregularities that exist in the interstellar medium, e.g. the distribution of HII regions and dense clouds. An unexplained feature of our observations, the rise of spin modulation and shift of phase of maximum brightness below $\sim$0.4 MHz, may be a result of such irregularities.

In the future there will be antenna arrays in space that will provide observations with much higher resolution than a simple dipole (e.g. Weiler 2000). Then the irregularities can be explored as a function of wavelength, i.e., as the observed emission originates closer and closer to the solar system. This may provide the opportunity to determine the properties of both the synchrotron radiation and the distribution of the warm ionized medium.

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