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THE NON-THERMAL EMISSIVITY OF THE GALACTIC DISK NEAR $l^{\mathrm{II}} = 140°$

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Summary

An area of sky containing the ionized hydrogen regions IC 1795, IC 1805 and IC 1848, and the supernova remnant HB 3, has been observed with the 10 MHz radio telescope at the Dominion Radio Astrophysical Observatory. The results imply that the brightness temperature of the non-thermal radio emission arising in the line of sight to the ionized hydrogen regions is between 85 000 °K and 140 000 °K at this frequency.

The mean non-thermal emissivity of the galactic disk in this direction ($l^{\mathrm{II}} \approx 140°$) is estimated to be between 4·5 and 9×10^{-41} W m^{-3} ster^{-1} Hz^{-1} at 10 MHz. This result is combined with measurements of the flux of primary cosmic ray electrons at the top of the Earth's atmosphere to estimate the strength of the interstellar magnetic field in this region of the disk.

It is suggested that the supernova remnant HB 3 is of exceptional linear size.

1. *Introduction.* At low radio frequencies H II regions become optically thick and may be observed in absorption against the galactic non-thermal background radiation. Observations of regions which fill an appreciable part of the antenna reception pattern and whose distances are known may be used to derive the non-thermal radio emissivity of the Galaxy in the directions concerned, and hence to find the strength of the galactic magnetic field by comparison with data on the cosmic ray electron component. An area of sky near $l^{\mathrm{II}} = 140°$ containing a number of extensive H II regions has been investigated with the 10·03 MHz telescope (Galt *et al.* 1967) at the Dominion Radio Astrophysical Observatory, Penticton, Canada, and the results obtained permit a new estimate of the non-thermal emissivity in this direction to be made.

2. *Observations.* The antenna is a T-shaped array of dipoles whose arms are used as an interferometer of zero spacing in the manner of a Mills Cross (Mills *et al.* 1958) to provide a reception pattern 2°·6 in right ascension by 2°·3 sec(z) in declination between the 3 dB points. The antenna differs from the original Mills Cross in that the power induced in the dipoles in the central area is divided equally between the feeder systems of the two arms by hybrid rings to provide the desired response to extended sources.

Observations are made by taking meridian drift curves with a fixed declination phasing of the reception pattern, and are normally made at night when ionospheric absorption is small. Three declination phasings may be used simultaneously to observe a strip of sky approximately 3°·5 wide in declination in every series of

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drift curves. An area of sky between right ascensions $01^{\mathrm{h}}\,50^{\mathrm{m}}$ and $03^{\mathrm{h}}\,50^{\mathrm{m}}$ and declinations $+56°$ and $+66°$ was observed on selected nights when ionospheric conditions were suitable, as described below.

The sensitivities of the receivers were calibrated before and after each series of drift curves by injecting a known noise power coherently into each arm of the antenna while observing the background radiation. The zero level was determined by replacing the antenna with resistors of the same impedance. A scale of flux densities was derived from the response to the noise calibration by observing the sources Cassiopeia A and Cygnus A, whose flux densities at 10 MHz are known (Bridle 1967a). A scale of brightness temperature was derived from the scale of flux density using the theoretical collecting area of the antenna. This scale applies to observations of both localized and extended features of the sky brightness distribution because the main lobe of the reception pattern contributes >98 per cent of the receiver output for most orientations of the reception pattern in the sky. This property arises because the voltage reception patterns of the two arms of the antenna have very nearly equal positive and negative sidelobes. The receiver output produced by power received in the sidelobes is therefore nearly zero except when they are directed towards intense discrete sources.

An uncertainty of order 25 per cent arises in making the theoretical estimate of the collecting area, due to the effects of interactions between the dipoles in the array. Observations of an area of sky away from the galactic plane were therefore made to verify that the adopted temperature scale is compatible with the results of other low-frequency surveys. The brightness of the radio background between 13 MHz and 178 MHz in areas of the sky away from the galactic plane may be represented by superimposing an anisotropic distribution of temperature with spectral index $\beta \approx 2{\cdot}4$ on an isotropic distribution with brightness temperature $(30 \pm 7)\,°\mathrm{K}$ at 178 MHz and spectral index $\beta = 2{\cdot}75$ (Bridle 1967b). The brightness temperature distribution at 178 MHz has a shallow minimum near $09^{\mathrm{h}}\,35^{\mathrm{m}}$, $+35°$, where the temperature is $(65 \pm 5)\,°\mathrm{K}$ (Baldwin, personal communication). On the above representation of the background spectrum this is equivalent to $(131\,000 \pm 26\,000)\,°\mathrm{K}$ at 10 MHz. The brightness temperature given for this area of sky by our calibration is $(140\,000 \pm 30\,000)\,°\mathrm{K}$, in satisfactory agreement with the predicted temperature.

Ionospheric effects were allowed for in all reductions of the 10 MHz data. The most severe effects were those of scintillation, which under adverse conditions could destroy the phase coherence of the radiation received by the antenna across its aperture so that the theoretical reception pattern was not achieved. These effects were eliminated by discarding observations made during periods when the recorded transits of intense sources showed severe scintillation. Ionospheric absorption was allowed for by making simultaneous total-power observations at the zenith with the north–south arm of the antenna alone. These observations have been made with the same receiving system and observing procedure for over one year and the absorption at any time may be estimated from them by a ‘ riometer ’ analysis (Hultqvist 1963). The background temperatures observed with this system on nights when ionospheric critical frequencies are <2 MHz are thought to be within 0·05 dB of the ‘ unabsorbed ’ temperatures. The absorption at other times may therefore be found by comparing the apparent temperatures with those observed on these occasions. The corrections applied to the present observations were typically of order 0·3 to 0·4 dB, and should be accurate to within ±0·2 dB.

Ionospheric refraction was allowed for by observing the apparent positions of intense discrete sources before and after observing the selected area. For observations obtained at night more than a few hours before sunrise or after sunset, only refraction in the north–south plane was significant in comparison with the width of the reception pattern; apparent declinations were typically adjusted by $+0^\circ{\cdot}5$.

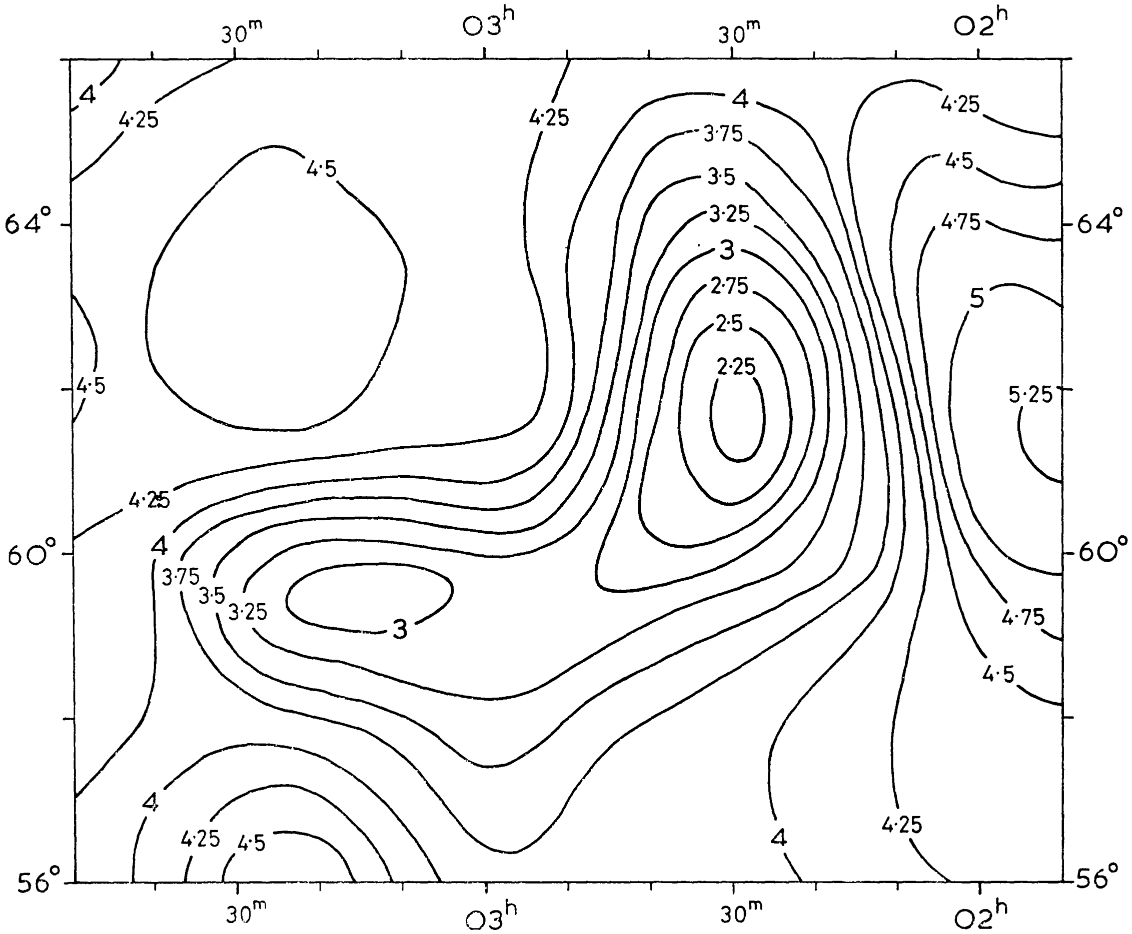

FIG. 1. *Contours of constant sky brightness temperature at* 10·03 *MHz in the area surveyed. The unit is* 100 000 °*K.*

3. ***Results.*** Three or four sets of drift curves were obtained at each of six declination phasings of the reception pattern within the selected area, and these were averaged after correction for ionospheric effects and for variations in the instrumental calibration to provide the map of sky brightness temperature shown in Fig. 1. The map shows a deep absorption feature at right ascension $02^{\mathrm{h}}\,29^{\mathrm{m}}$, declination $+61^\circ{\cdot}5$, close to the centre of an emission nebula catalogued by Lynds (1965). The nebula is 2° by 1° in extent on the prints of the National Geographic Society–Palomar Observatory Sky Survey and contains the bright nebulae IC 1795 (Westerhout 3) and IC 1805 (Westerhout 4). The absorption feature is significantly extended in both right ascension and declination, the extension to the south–east being in the direction of the nebula IC 1848. A second absorption feature centred on right ascension $03^{\mathrm{h}}\,14^{\mathrm{m}}$, declination $+59^\circ{\cdot}4$ coincides with the nebula Sharpless 202.

4. *Theory.* The sky brightness temperature in the direction of an H II region is given by the well-known relation

$$T(\nu) = T_{\mathrm{FG}}(\nu) + T_K(1 - e^{-\tau(\nu)}) + T_{\mathrm{BG}}(\nu)e^{-\tau(\nu)} \tag{1}$$

where $\tau(\nu)$ is the optical depth of the region at the frequency ν, T_{FG} and T_{BG} the brightness temperatures of the 'foreground' and 'background' non-thermal emission, i.e. of the radiation originating in front of and behind the ionized hydrogen respectively. T_K is the kinetic temperature of the ionized hydrogen. The expression for the linear absorption coefficient of a plasma derived by Scheuer (1960) gives the following formula for the optical depth $\tau(10)$ of a region with emission measure E cm^{-6} pc at 10 MHz:

$$\tau(10) = 4 \times 10^3 E T_K^{-3/2}. \tag{2}$$

T_K is typically ≈ 8000°K in an ionized hydrogen region (O'Dell 1966) so that $\tau(10) \approx 7 \times 10^{-3}E$. The third term in equation (1) is therefore $< 0.1 T_{\mathrm{BG}}$ if $E > 340$ cm^{-6} pc and $< 0.01 T_{\mathrm{BG}}$ if $E > 640$ cm^{-6} pc. Ionized hydrogen which is visible on the prints of the National Geographic Society–Palomar Observatory Sky Survey has $E \gtrsim 300$ cm^{-6} pc and will therefore be almost completely opaque to the background radiation at 10 MHz. The sky brightness temperature in the direction of such gas will be nearly equal to

$$T^*(10) = T_{\mathrm{FG}}(10) + T_K. \tag{3}$$

T^* represents the observed brightness temperature if the opaque region fills the reception pattern of the telescope, but in general some areas of the reception pattern will contain background radiation which has not been absorbed by the region under investigation, and $T_{\mathrm{obs}} > T^*$.

The exact distribution of absorbing material in a given area of the sky may in principle be found from studies of the area concerned at high radio frequencies or in the visible. Surveys at high radio frequencies have not generally been carried out with sufficient sensitivity to detect ionized hydrogen with an emission measure ≈ 300 however, and optical data may be affected by interstellar obscuration. In what follows we shall attempt to infer the distribution of absorbing material from the 10 MHz observations themselves.

5. *The foreground temperature near IC* 1805. The extension of the absorption feature centred near IC 1805 suggests that the opaque region producing it fills an appreciable part of the 10 MHz reception pattern when this is directed to the centre of the feature. The opaque region cannot fill the pattern completely however, for if it did the variation of the observed brightness near the centre of the feature would be slow, whereas the actual variation with right ascension is as rapid as the reception pattern permits.

The discrete source HB 3, which is thought to be a supernova remnant (Caswell 1967), is at right ascension 02$^{\mathrm{h}}$ 15$^{\mathrm{m}}$, declination +61°·5, but is not apparent on the map. The flux density of HB 3 expected from extrapolation of Caswell's measurements on the assumption that the spectrum has no intrinsic low-frequency cut-off is 8×10^{-24} W m^{-2} Hz^{-1} at 10 MHz. This assumption will be discussed later in this paper. A source with this flux density would be apparent on the 10 MHz map, and it may be inferred that the opacity surrounding IC 1805 extends at least as far as the line of sight to HB 3, and also that HB 3 is further from us than the opaque region.

The distances to the various nebulae in the field may be estimated from the distance moduli ($m-M$) of their exciting stars (Hiltner 1956; Moriyama 1961), which are listed in Table I. The three nebulae IC 1795, IC 1805 and IC 1848 lie at similar distances, and all the H II in the field will be assumed to lie at the distance corresponding to the mean distance modulus of the thirteen exciting stars. This is $\overline{(m-M)} = 11{\cdot}5 \pm 0{\cdot}2$, corresponding to a distance of $(2{\cdot}0 \pm 0{\cdot}1)$ kpc.

TABLE I

Distance moduli of the exciting stars

Nebula	Exciting stars	($m-M$)	$\overline{(m-M)}$ for nebula
IC 1795	+61° 411	11·4	11·4
	+60° 497	11·2	
	+60° 498	12·0	
	+60° 501	12·4	
IC 1805	HD 15558	10·4	11·5 ±0·3
	HD 15570	11·5	
	HD 15629	11·3	
	+60° 512	12·0	
	+59° 562	12·5	
	+60° 586	11·7	
IC 1848	HD 17505	10·0	11·5 ±0·4
	HD 17520	11·5	
	E 237007	11·7	

Models of the size and shape of the opaque region were convolved with the reception pattern of the instrument to reproduce the 10 MHz measurements. The models may all be described as follows:

(i) The brightness temperature of the total background radiation was assumed to vary between 400 000 °K and 550 000 °K across the map, as indicated by the temperatures measured away from the absorption features. The radiation from the source HB 3 was included as 'background radiation' and assumed to contribute a flux density of 8×10^{-24} W m^{-2} Hz^{-1} integrated over the source.

(ii) The opaque region was assumed to have a sharply defined 'edge', within which only foreground radiation and thermal emission are observed, and outside which there is no absorption of the background. This assumption is justified because the transmission of the background depends exponentially on the emission measure of the ionized hydrogen in the line of sight, and further because the boundaries of ionized hydrogen regions are sharply defined.

(iii) The brightness temperature $T^*(10)$ was left unspecified and was adjusted for the best fit to the observed contours.

The absorption due to Sharpless 202 was not considered in the model-fitting, which was confined to the contours surrounding IC 1805. A range of models may fit the contours. In all of them the opaque region is ~4° across in declination and centred on the extended nebula catalogued by Lynds (1965). For widths in right ascension ranging from 3° to 4° a satisfactory fit is obtained with T^* being 95 000 °K to 150 000 °K accordingly, corresponding to $T_{FG} \approx 85\,000$ °K to 140 000 °K if we allow for the thermal emission from the nebulae. The contours cannot be fitted if the width in right ascension lies outside these limits.

The main source of error in this result is the uncertainty in the proportion of the reception pattern filled by the opaque material; the probable error in determining the brightness temperature scale of the observations is relatively insignificant. A potential source of error is the effect of sidelobe responses of the antenna; the theoretical sidelobe responses have been taken into account in the above calculation, but the actual sidelobe distribution could be significantly different from that assumed. The error arising from this is unlikely to be comparable with that already given.

6. *The non-thermal emissivity.* The magnitude of T_{FG} is of particular interest as the distance to the absorbing material is known. The adopted distance of 2 kpc gives the following results for the mean emissivity in the line of sight:

$$T_{FG} = 85\,000\,^\circ\mathrm{K}, \quad \bar{\eta}(10) = 4{\cdot}3 \times 10^{-41}\ \mathrm{W\,m^{-3}\,ster^{-1}\,Hz^{-1}}$$

$$T_{FG} = 140\,000\,^\circ\mathrm{K}, \quad \bar{\eta}(10) = 7 \times 10^{-41}\ \mathrm{W\,m^{-3}\,ster^{-1}\,Hz^{-1}}.$$

It is possible that these results may not represent the true mean non-thermal emissivity of the interstellar material because of the effect of diffuse ionized material which may be present along the line of sight. The magnitude of this effect may be estimated from observations of discrete sources near the selected area in the galactic disk. Observations of absorption in the low frequency spectra of the supernova remnants Cas A (Bridle 1967a) and 3C 10 (Bridle 1967c), whose distances are known, indicate that the mean optical depth of the interstellar medium at latitudes of 1° to 2° in this region of the disk is 0·25 to 0·30 $\mathrm{kpc^{-1}}$ at 10 MHz. If the non-thermal emission and the ionized material are both uniformly distributed, the above estimates of the interstellar emissivity would be ≈ 25 per cent too low because of this effect.

If all the sources of error we have discussed are taken into account, we may conclude that the mean non-thermal emissivity of the interstellar material at 10 MHz lies between the limits $4{\cdot}5 \times 10^{-41}$ and $9 \times 10^{-41}\ \mathrm{W\,m^{-3}\,ster^{-1}\,Hz^{-1}}$, the most probable value being $6{\cdot}5 \times 10^{-41}\ \mathrm{W\,m^{-3}\,ster^{-1}\,Hz^{-1}}$.

We have derived the mean value of the non-thermal emissivity which would apply if the emission were uniformly distributed in the galactic disk. If however the emission were concentrated entirely within the spiral arms, the emissivity will have been under-estimated. At the assumed distance of 2 kpc, the ionized hydrogen regions we have considered lie on the nearer edge of the Perseus spiral arm, so that in a ‘ spiral arm ’ model of the emission the observed foreground radiation would be contributed by the local arm alone. Taking the thickness of this arm in the galactic disk as 500 pc, the most probable value of its emissivity on this model is $\eta_{\mathrm{arm}} = 2 \times 10^{-40}\ \mathrm{W\,m^{-3}\,ster^{-1}\,Hz^{-1}}$. Further observations of absorption in ionized hydrogen regions at various distances from the Sun may define the variation of the non-thermal emissivity with distance, and thus enable us to distinguish between the ‘ uniform ’ and the ‘ spiral arm ’ models of the emission.

These results are compatible with those obtained by Mills (1959) for the non-thermal emissivity of the inner regions of the galactic disk, if the spectral index of the non-thermal radiation between 10 MHz and 85 MHz is $\alpha \approx 0{\cdot}4$.

7. *The interstellar magnetic field.* The above estimates of the non-thermal emissivity may be used to derive the value of the magnetic field strength along the line of sight to the opaque region. Various authors (LeRoux 1961; Ginzburg & Syro-

vatskii 1964) have shown that in a region containing relativistic electrons with a differential energy spectrum

$$dn(E) = n_0 E^{-\gamma}\, dE \tag{4}$$

the synchrotron emissivity η is related to the magnetic field strength B by

$$\eta(\nu) \propto f(\gamma)(B \sin\theta)^{(\gamma+1)/2} n_0 \nu^{-(\gamma-1)/2}. \tag{5}$$

In this expression $f(\gamma)$ is a numerical factor which varies slowly with γ, and θ is the angle between the magnetic field direction (assumed constant throughout the region) and the line of sight. n_0, the number of electrons per unit volume with unit energy, may be estimated from measurements of the flux of primary cosmic-ray electrons at the top of the Earth's atmosphere. The value of γ may be obtained from the observed differential energy spectrum of these electrons, but a more accurate value may be derived from the observed galactic radio spectral index, using equation (5). The radio data are more suitable for this purpose partly because of their higher accuracy, and partly because the observed cosmic-ray spectrum may be affected at low energies by solar exclusion of the galactic electrons. We shall attempt to minimize the uncertainty in this calculation arising from heliocentric effects by taking $\gamma = 1{\cdot}8$ from radio observations (Bridle 1967b) and normalizing the assumed cosmic-ray energy spectrum to measurements at $E = 4{\cdot}5$ GeV (Agrinier *et al.* 1964; Bleeker *et al.* 1965). At this energy the heliocentric effects should be negligible (Webber & Chotkowski 1966), particularly near the time of minimal solar activity when the measurements were made. The direction of the magnetic field in the interstellar medium along the line of sight was taken as $\theta = 90°$ from the analysis of radio and optical polarization data by Bingham & Shakeshaft (1967). With these assumptions, and allowing for the increase in γ at the highest energies implied by the steepening of the radio spectrum at frequencies above 200 MHz (Bridle 1967b; Howell & Shakeshaft 1967), the mean emissivity derived above gives a mean magnetic field strength in the line of sight of $(6 \pm 2) \times 10^{-6}$ gauss. The error quoted includes the effect of the experimental uncertainty in the cosmic-ray electron flux. If the non-thermal emission is assumed to be concentrated within the spiral arms, the results imply a magnetic field strength B_{arm} of $(1{\cdot}6 \pm 0{\cdot}5) \times 10^{-5}$ gauss.

It must be noted that the value obtained for B depends on the value of γ adopted, being smaller for larger values of γ. The value $\gamma = 1{\cdot}8$ used here is significantly smaller than those used by other workers (Webber & Chotkowski 1966; Felten 1966) and is based on more recent radio data than was considered by them.

8. *The source HB* 3. The apparent flux density of HB 3 at 10 MHz is $< 3 \times 10^{-24}$ W m^{-2} Hz^{-1}. We have taken this to imply that the source is located beyond the ionized hydrogen regions considered. Alternative interpretations would be that the source exhibits an intrinsic low-frequency cut-off occasioned by (a) absorption by ionized hydrogen within the supernova shell itself, (b) the Tsytovich–Razin effect, or (c) synchrotron self-absorption. If the supernova shell were a few parsecs thick and contained a magnetic field of strength $\approx 10^{-5}$ gauss, mechanisms (a) and (b) would both require an implausibly high electron density to be present in the shell. The mean interstellar electron density in this region of the galactic disk may be estimated from our value of the interstellar optical depth at 10 MHz. If the kinetic temperature $T_K = 10^4$ °K in the interstellar medium, $\tau(10) = 0{\cdot}25$ kpc^{-1} corresponds to a mean number density of electrons of 0·2 cm^{-3}, using

equation (2). Mechanisms (a) and (b) would therefore only be significant in HB 3 if the compression of the interstellar medium in the shell were of order 100 : 1, or if the source were located in a region of considerably enhanced electron density. Mechanism (c) would only be important if most of the radio emission arose in regions of the source with angular diameters $\lesssim 2''$ arc, which is ruled out by the absence of intense sources in this area of the 4C survey (Gower, Scott & Wills 1967). The conclusion that the source lies beyond the opacity surrounding IC 1805 seems preferable to any of these alternatives.

At 178 MHz the source has a shell structure $1^\circ\cdot 5$ in diameter (Caswell 1967). If its distance is $\gtrsim 2$ kpc, its linear diameter must therefore be $\gtrsim 50$ pc, so that the source is an extremely extended remnant similar to the Cygnus Loop.

9. *Acknowledgments.* The experimental programme was carried out during a most pleasant period while the author was a guest of the Dominion Radio Astrophysical Observatory. This work was performed during the tenure of a Science Research Council Research Fellowship.

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Note added in proof. A series of improved observations has recently been made with the 10·03 MHz telescope, and indicates that the absorption feature centred on 1C 1805 is not so deep as shown in Fig. 1. Preliminary analysis of the new data suggests that our values for the foreground temperature T_{FG}, and the derived emissivities, should be increased by about 50 per cent.