# A RADIO SURVEY OF THE SOUTHERN MILKY WAY AT A FREQUENCY OF 1440 Mc/s

## II. THE CONTINUUM EMISSION FROM THE GALACTIC DISK

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*Summary*

The 1440 Mc/s survey (Part I of this series) has been used in conjunction with the 85·5 Mc/s survey of Hill, Slee, and Mills (1958) to delineate the distribution of the thermal and nonthermal radiation from the disk component of the Southern Milky Way and so complete an investigation commenced by the Northern Hemisphere observers Westerhout (Leiden) and Large, Mathewson, and Haslam (Jodrell Bank). Results of the analysis show an intense concentration of ionized hydrogen in an irregular spiral structure in the inner regions of the Galaxy. From $l^{\mathrm{II}}=256°$ to 88°, good agreement was obtained between the longitudes at which concentrations of neutral hydrogen were found to occur from H-line studies and the longitudes at which the ionized hydrogen was concentrated. The steps in the longitude distribution of the 85·5 Mc/s radiation which Mills used to delineate the spiral arms of the Galaxy were not all visible in the longitude distribution of the nonthermal component obtained from this present analysis. It is believed that three of Mills's steps are thermal in origin.

### I. INTRODUCTION

In Part I of this series (Mathewson, Healey, and Rome 1962), the results of a radio survey of the Southern Milky Way at 1440 Mc/s with a resolution of 50′ of arc were described. In Part I the isophotes were presented and the positions of the radio sources resolved from the background emission were listed, together with their spectral characteristics determined by comparison of their intensities at 1440 and 85·5 Mc/s (Hill, Slee, and Mills 1958). An investigation has now been made of the more extended emission from the galactic disk (Mills 1959; also Part I of this series loc. cit.).

The spectral characteristics of the disk emission of the Northern Milky Way have already been studied by Westerhout (1958) using his 1390 Mc/s observations and the Sydney 85·5 Mc/s survey. He found that in latitude the nonthermal component has an average half-width of 4°·2 whereas the thermal component is only 1°·6 wide. He also discovered that the longitude distribution of the thermal radiation has a maximum at $l^{\mathrm{II}}=26°$. Assuming axial symmetry, he suggested that there was a ring of ionized hydrogen about the galactic centre of radius 3·5 kpc and thickness 200 pc. Large, Mathewson, and Haslam (1961) compared in detail their Jodrell Bank 408 Mc/s results with the Sydney 85·5Mc/s survey (Hill, Slee, and Mills 1958) and the Leiden 1390 Mc/s survey (Westerhout 1958) producing isophotes of the thermal and nonthermal background radiation

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for the Northern Milky Way which confirmed Westerhout's results of the concentration of ionized hydrogen at $l^{\mathrm{II}}=26°$ and its very narrow distribution in latitude. They also compared the low resolution (3°·3 aerial beam at half-power points) 600 Mc/s survey of Piddington and Trent (1956) with the Sydney 85·5 Mc/s survey and found a peak in the thermal emission at $l^{\mathrm{II}}=335°$ which gave support to Westerhout's assumption of a radial distribution of ionized hydrogen at 3·5 kpc from the galactic centre. However, because of the poor resolution of the 600 Mc/s survey a detailed distribution of the thermal and nonthermal components of the background emission could not be obtained for the Southern Milky Way. Therefore it was decided to compare the 1440 Mc/s survey (Part I of this series) with the Sydney 85·5 Mc/s survey, both made with a resolution of 50′ of arc, and extend to the Southern Milky Way this line of investigation initiated by northern-hemisphere observers and so complete the half-finished picture of the distribution of thermal and nonthermal radio emission from the galactic disk. This paper presents the results of this analysis.

## II. Separation of the Thermal and Nonthermal Components

### (a) *Theory*

Westerhout (1958) has shown that if certain assumptions are made then the total brightness temperature ($T$) at a frequency ($f$) of a mixture of thermal and nonthermal sources is given by

$$T(f)=(T_e+T_n/\tau)(1-e^{-\tau}), \tag{1}$$

where $T_e$ is the electron temperature of the thermal material, $\tau$ is its optical depth at a frequency ($f$), and $T_n$ is the brightness temperature of the nonthermal emission at a frequency ($f$) in the absence of absorption.

For $\tau \ll 1$, equation (1) reduces to

$$T(f)=\tau T_e+T_n, \tag{2}$$

where $\tau T_e$ represents the contribution to the brightness temperature by the thermal emission.

At 1440 Mc/s the observed brightness temperature may be represented by (2) and at 85·5 Mc/s by (1). In applying these equations to calculate the relative amounts of thermal and nonthermal emission at 1440 Mc/s, the optical depth $\tau$ has been taken to be inversely proportional to the square of the frequency, and the nonthermal brightness temperature to have a spectral index $\beta$ ($\alpha$ the more commonly used spectral index of flux density equals $\beta+2$), thus:

$$\left.\begin{aligned}\tau &\propto f^{-2},\\ T_n &\propto f^{\beta}.\end{aligned}\right\} \tag{3}$$

The assumptions on which this analysis is based are now briefly discussed:

(i) The variation of spectral index across the galactic plane is due to the emission from ionized hydrogen.

(ii) The electron temperature of the ionized hydrogen is constant and equal to $10^4$ °K. Unless the electron temperature is grossly different from this value, it scarcely affects the analysis.

(iii) The sources of thermal and nonthermal emission are well mixed in the line-of-sight. This condition is important when $\tau > 0 \cdot 5$. As the maximum value of $\tau$ at $85 \cdot 5$ Mc/s reached in the analysis is only $0 \cdot 3$, a relaxation of the "complete-mixing" model is possible without introducing any great error into the result.

(iv) The nonthermal sources do not appreciably absorb incident radiation.

(v) The spectral index of the nonthermal radiation is unvarying with frequency between 1400 and $85 \cdot 5$ Mc/s.

The value of the nonthermal flux-density spectral index ($\alpha$) has been taken to be $-0 \cdot 6$. This is the value used by Westerhout and Large, Mathewson, and Haslam in their analysis. Also Komesaroff (1961) compared the intensities of points 5° off the galactic plane obtained from surveys made at six frequencies lying between 1390 and $19 \cdot 7$ Mc/s and concluded that a spectral index of $-0 \cdot 6$ for the nonthermal background emission agreed most satisfactorily with the observations.

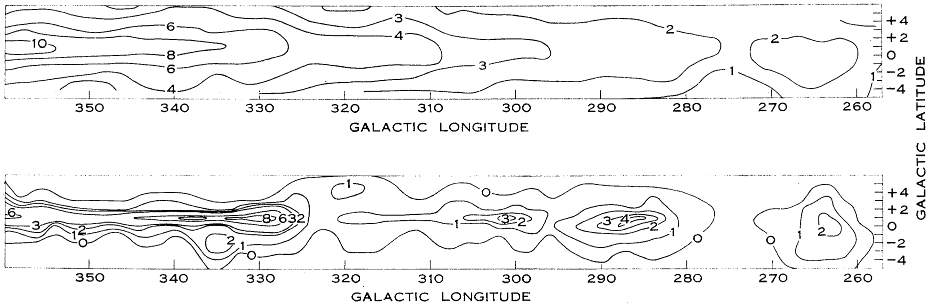


Fig. 1.—Isophotes showing the distribution of nonthermal (top) and thermal (bottom) radiation at 1440 Mc/s in the disk component of the Southern Milky Way. The numbers on the contours represent the brightness temperature in degrees Kelvin.

### (b) *Method of Analysis*

(i) *Isophotes.*—Large, Mathewson, and Haslam (1961) presented isophotes showing the distribution of thermal and nonthermal background radiation at 408 Mc/s for the Northern Milky Way. Combining the 1440 Mc/s survey (Part I) with the $85 \cdot 5$ Mc/s survey, similar isophotes have been determined for 1440 Mc/s for the Southern Milky Way which are shown in Figure 1.

Before proceeding with the separation of the observed radiation into thermal and nonthermal components it was necessary to estimate the zero level of brightness temperature of the 1440 Mc/s survey. The temperatures indicated by the 1440 Mc/s isophotes are measured above points about 10° from the galactic plane where the radiation is thought to be entirely nonthermal. If a flux-density spectral index of $-0 \cdot 6$ is accepted for this radiation, an absolute brightness temperature of $1 \cdot 5$ °K is computed from the Sydney $85 \cdot 5$ Mc/s temperatures for these galactic latitudes. Westerhout (1958) also estimates that to obtain absolute brightness temperatures, $1 \cdot 5$ °K needs to be added to his Northern Milky Way 1390 Mc/s isophotes, the temperatures of which are measured above reference regions about 10° from the galactic plane.

To construct the thermal and nonthermal isophotes shown in Figure 1, a grid of points was drawn on the 1440 Mc/s and 85·5 Mc/s surveys at 2° interval in longitude and 1° interval in latitude. The contribution from any discrete source was not included and at each point the " background temperature " was read for each frequency of observation. These temperatures which were taken to represent the distribution of radiation from the large-scale features of the Galaxy, were tabulated and zero-level corrections of 1·5 °K were added to the 1440 Mc/s values. The relative amounts of the thermal and nonthermal emission at 1440 Mc/s at each point on the grid were calculated on SILLIAC, the computer of the University of Sydney, using equations (1), (2), and (3) of the present paper.

(ii) *The Galactic Plane Scan.*—Figure 3 (Part I) shows the 1440 Mc/s record obtained by scanning the 60-ft paraboloid along the galactic plane from $l^{II}=256°$ to 88° and the variation in intensity of the 85·5 Mc/s radiation along the galactic plane from $l^{II}=256°$ to 45°, derived from the 85·5 Mc/s isophotes of Hill, Slee,

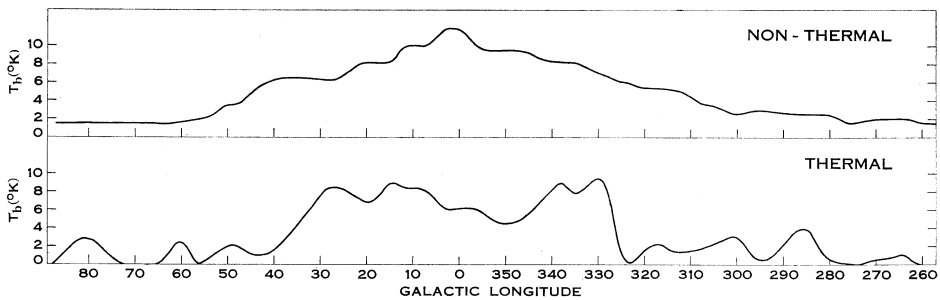


Fig. 2.—The longitude distribution of the nonthermal (top) and thermal (bottom) components of the 1440 Mc/s galactic background radiation along the galactic plane from $l^{II}=256°$ to 88°.

and Mills (1958). The discrete sources seen lying above the background were removed by drawing a smooth curve through the minima of the two radio profiles. The longitude distribution of the 1440 Mc/s thermal and nonthermal components of the background emission along the galactic plane was then calculated from the intensities of the two lower envelopes at 1440 Mc/s and 85·5 Mc/s using the theory given above. The results are presented in Figure 2. As the 85·5 Mc/s survey only extended to $l^{II}=45°$ the Jodrell Bank 408 Mc/s results (Large, Mathewson, and Haslam 1961; Mathewson, Large, and Haslam 1960) were used together with the 1440 Mc/s scan to continue the spectral analysis up to $l^{II}=88°$. As a check on the results obtained using the 1440 and 85·5 Mc/s intensities, the separation into thermal and nonthermal components of the background emission from $l^{II}=356°$ to 45° along the galactic plane was also made comparing the 1440 and 408 Mc/s temperatures. No significant difference was found between the two comparisons.

At 1440 and 408 Mc/s the optical depth is very small ($\tau \ll 1$) and equation (1) holds for any distribution of the sources of thermal and nonthermal radiation along the line-of-sight. Even at 85·5 Mc/s where the optical depth reaches 0·3 in regions close to the galactic centre, equation (1) based on the assumption that the thermal and nonthermal emitting regions are well mixed is still approximately correct even for fairly large departures from complete mixing. However, at very low frequencies, where the optical depth becomes large, gross departures from the " complete-mixing " model would be expected to show in the results. Therefore it was interesting to find that similar results for the thermal–nonthermal separation of the background emission along the galactic plane shown in Figure 2 were obtained comparing the 19·7 Mc/s intensities (Shain, Komesaroff, and Higgins 1961) with the 1440 Mc/s intensities. Komesaroff (1961) also found by comparing intensities at 1390, 85·5, and 19·7 Mc/s at five different longitudes in the Northern Milky Way which were relatively free of discrete sources that the complete-mixing model gave the best agreement with the observed results. The results of this analysis showing the distribution of thermal and nonthermal radio emission in regions close to the galactic plane will now be discussed.

## III. Discussion of Results

### (a) *Thermal Disk Component*

A fairly complete picture of the integrated emission from large-scale distributions of ionized hydrogen lying along the Milky Way is now available from examination of Figure 2 (thermal emission along the galactic plane from $l^{\text{II}}=256°$ to 88°), Figure 1 (1440 Mc/s thermal isophotes of the Southern Milky Way), and the paper by Large, Mathewson, and Haslam (1961) (408 Mc/s thermal isophotes of the Northern Milky Way). From these data we conclude that the thermal emission from the Galaxy may be divided into two parts : (i) a central component and (ii) a spiral arm component.

(i) *Central Component.*—The most outstanding feature of the thermal disk component is the high concentration of emission in the inner regions of the Galaxy. In longitude, a relatively intense " plateau " of radio emission runs out to some 30° either side of the galactic centre whereupon the radiation drops remarkably rapidly to low values and apart from some small intensity fluctuations remains at a very low level. This " plateau " is clear evidence for a concentration of ionized gas in the central regions of the Galaxy and we shall describe the emission from it as the " central component ". Superimposed on this central " plateau " are relatively small-scale fluctuations which produce peaks in the thermal radio emission at $l^{\text{II}}=330°$, 338°, 14°, 27°. The 1440 Mc/s brightness temperature at the position of these peaks rises to about 9 °K. There is a broad minimum at $l^{\text{II}}=350°$ where the brightness temperature drops to about 5 °K. The latitude distribution of this inner concentration of thermal emission is strikingly narrow, the width at half-intensity points being only about 1°·5.

It is quite apparent that a new large-scale feature of galactic radio emission has emerged from this analysis. Westerhout first discovered the Northern Milky Way section of this component and also predicted that it would lie fairly symmetrically disturbed about the galactic centre which this analysis has confirmed. He interpreted this phenomenon as a ring of ionized hydrogen about the galactic centre of radius 3·5–4 kpc and about 200 pc thick.

At this stage we should recall the rather subjective method by which the discrete radio sources are separated from the background emission and the assumptions that were made to separate the thermal and nonthermal components of the background emission. Consequently the interpretation of the results should not be pushed too hard but only the broad details concentrated upon. It is noted that an emitting region in the form of a ring would give two maxima in the directions where the line-of-sight is tangential, with a minimum between. A disk would give a single peak in the direction of the centre. The actual form is complex and does not conform with either of these simple hypotheses. The results could fit a bar running approximately normal to our line of sight or perhaps several rings concentric about the centre. Perhaps the simplest interpretation is that the ionized hydrogen in this inner region is concentrated in an irregular spiral structure which produces peaks in the thermal emission at $l^{II}=330°$, 338°, 14°, 27°, where the line-of-sight is tangential to the arms.

This inner region is of particular interest, for H-line studies have shown that the neutral hydrogen is expanding outwards from the galactic centre at velocities of 150 km/sec and, at a distance of about 4 kpc, appears to slow down to 50 km/sec and partake in the general galactic rotation. If these inner spiral arms containing hydrogen are expanding rapidly outwards the ionization of the hydrogen may be produced by collisional excitation such as in the expanding shells of supernova, e.g. the Cygnus Loop, rather than by radiative excitation by ultraviolet light from O and B stars.

(ii) *Outer Spiral Arm Component.*—Outside the high intensity central concentration of emission there are some relatively low intensity peaks in the longitude distribution of the thermal disk radiation (Fig. 2) occurring at $l^{II}=264°$, 286°, 301°, 317°, 49°, 60°, and 80°. The thermal isophotes of the disk in Figure 1 also show a definite bunching of radiation about these longitude positions in the Southern Milky Way, the half-intensity widths in latitude being about 3°, much broader than the narrow cross section of the Central Component. As it is reasonable to assume that most of the ionized hydrogen is confined to the spiral arms of the Galaxy and that the thermal radiation emitted would be isotropic, then these maxima in the thermal component may tentatively be identified with directions in which the line-of-sight is tangential to the various spiral arms.

A model of the Galaxy delineating the spiral arms has been constructed from H-line studies (Oort 1959) and it is interesting to compare the longitudes at which the line-of-sight is tangential to the arms as depicted from the concentrations of neutral hydrogen to the longitudes at which concentrations of ionized hydrogen have been found to occur in the present studies. This comparison is displayed in Figure 3. (The position of the peaks found in the emission from the Central thermal Component are also included.) The agreement is remarkably good apart from two positions given by the thermal component at $l^{II}=301°$ and 60° which have no counterpart in the H-line picture. In general, the longitude positions given by the thermal component either agree with the H-line positions or lie a few degrees closer to the galactic centre. This may be fortuitous, although it would be expected if the spiral arms were expanding, carrying the neutral hydrogen with them and leaving behind the formed stars which excite and form the core of the large HII complexes.

The 1440 Mc/s flux densities (Westerhout 1958 ; Part I of this series) of the discrete radio sources lying between $b^{\mathrm{II}}=\pm 6°$ and $l^{\mathrm{II}}=256°$ to 88° have been integrated over 5° intervals in longitude and the results displayed in the form of a histogram in Figure 4. It is apparent that a clustering of the sources occurs at longitudes 263°, 287°, 309°, 334°, 351°, 13°, 27°, 48°, and 80°. These have been added to the diagram in Figure 3 (bottom). There appears little doubt that in the Galaxy somewhere along the lines-of-sight marked by $l^{\mathrm{II}}=263°$, 286°,

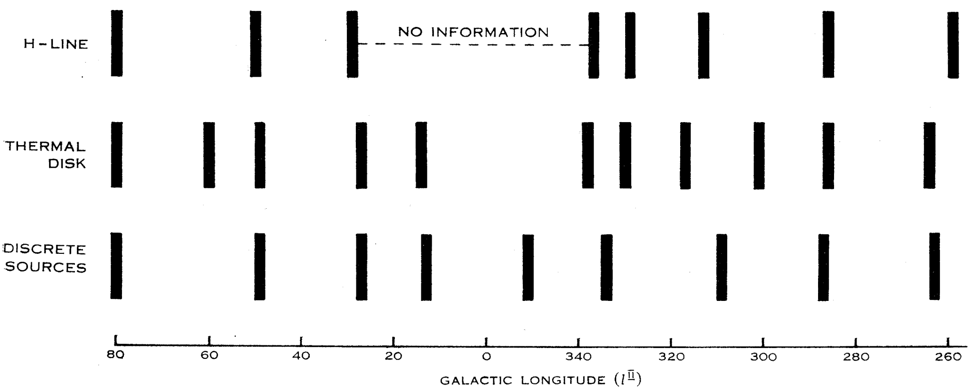


Fig. 3.—Comparison of the galactic longitudes along the galactic plane at which concentrations of neutral hydrogen are expected from H-line studies (top) to those where concentrations of ionized hydrogen are predicted from the present analysis of the thermal disk component (centre). At the bottom are shown the longitudes at which the discrete sources tend to cluster (Fig. 4).

330°, 338°, 14°, 27°, 49°, and 80° there are concentrations of neutral hydrogen, ionized hydrogen, and thermal and nonthermal discrete sources although at the moment no attempt has been made to fit a regular spiral pattern to these directions.

Figure 1 shows two weak extended regions of thermal emission at 1440 Mc/s centred on $l^{\mathrm{II}}=335°$, $b^{\mathrm{II}}=-3°$ and $l^{\mathrm{II}}=320°$, $b^{\mathrm{II}}=+3°$. The 85·5 Mc/s isophotes of Hill, Slee, and Mills (1958) show evidence of absorption in the first region against a background temperature of 7000 °K which is rather unusual as the electron temperature of concentrations of ionized hydrogen in the Galaxy is generally accepted to be $10^4$ °K, in which case the region should be seen in emission (see Aller 1953 ; also Section VII, Part I of this series). In the 19·7 Mc/s isophotes of Shain, Komesaroff, and Higgins (1961), the second region ($l^{\mathrm{II}}=320°$, $b^{\mathrm{II}}=+3°$) is found to lie at the top of a band of absorption which cuts the galactic plane at right angles at $l^{\mathrm{II}}=320°$ and extends out to high latitudes on either side of the plane. Thus these high frequency observations give some support to the lower frequency ones.

*(b) Nonthermal Background Radiation*

Westerhout (1958) and Large, Mathewson, and Haslam (1961) have found that the distribution of the thermal component of the disk radio emission of the Northern Milky Way is markedly different to the nonthermal. A similar difference is also noticeable in the Southern Milky Way, which is shown in Figures 1 and 2. In longitude, the nonthermal radiation falls off in a series of steps from the galactic centre to a relatively low intensity at about 60° either side of the centre and in latitude, it has a width at half-intensity points of about $\pm 3°$.

Mills (1959) has advanced the interesting theory that the nonthermal radiation originates mainly in the spiral arms and he has identified the abrupt changes of intensity seen in the longitude distribution of the 85·5 Mc/s background

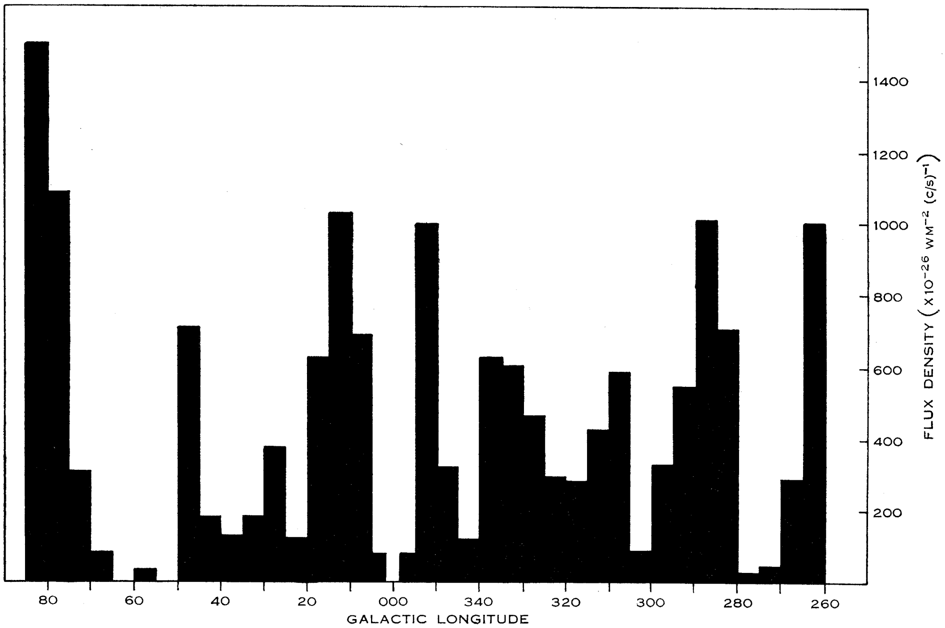


Fig. 4.—The integrated 1440 Mc/s flux densities of the discrete radio sources lying between $b^{\text{II}} = \pm 6°$ and $l^{\text{II}} = 256°$ to 88° in 5° intervals in longitude.

radiation, which is largely nonthermal in origin, with directions in which the line-of-sight is tangential to the spiral arms. Assuming the synchrotron theory of the origin of the nonthermal radiation, Hanbury Brown and Hazard (1960) have shown that these steps observed are possible and their shape and magnitude depend on the degree of alignment of the magnetic field along the spiral arms. Mills found that the steps in the 85·5 Mc/s radiation occurred at $l^{\text{II}} = 264°$, 280°, 309°, 327°, 337°, 344°, 14°, 23°, 40°, and 80° which are not all visible in the longitude distribution of the nonthermal component in Figure 2 where the steps are seen to be present at $l^{\text{II}} = 307°$, 329°, 343°, 14°, 24°, and 46°. It is possible that steps seen at 85·5 Mc/s at $l^{\text{II}} = 280°$, 337°, and 40° are thermal in origin and that Mills has included these with features of the nonthermal distribution.

Even so the positions of the steps in the nonthermal component do not agree well with those of the peaks in the thermal disk radiation (Fig. 3) which also were identified with directions in which the line-of-sight is tangential to the spiral arms. Because of the uncertainty in interpretation of the steps in the nonthermal radiation due to the directional properties of the synchrotron emission and dependence on the alignment of magnetic fields in the spiral arms, more confidence is placed in the location of the arms by the maxima in the thermal component which is isotropic and therefore simpler to interpret.

## IV. Acknowledgments

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