A WARM MAGNETOACTIVE PLASMA IN A LARGE VOLUME OF SPACE

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1. INTRODUCTION

This paper will show that a diffuse ionized warm gas fills a large volume of space in the general direction of Radio Loop II. There are three types of observational evidence: Faraday rotation measures (RM's) of extragalactic sources; emission measures (EM's) derived from the Hα emission line in the diffuse interstellar medium; and magnetic field strengths in HI clouds derived from Zeeman splitting observations.

2. OBSERVED CHARACTERISTICS

The region of interest, 'Region A' of Simard-Normandin and Kronberg (1980), occupies 80° to 130° in Galactic longitude and about -40° to +10° in latitude. This is a very large solid angle, a bit more than one steradian. All extragalactic radio sources within this region have large negative RM's and none have small RM's. This implies that the region contains a magnetoactive plasma smooth in the large-scale, without small-scale structure. RM's in the opposite direction of the sky tend to be positive, instead of negative, which might imply that Region A lies immediately adjacent to the Sun. However, the RM's are much smaller in magnitude than in Region A, which might mean simply that the gas is less highly ionized than that in Region A, or alternatively that Region A lies some distance from the Sun. Typical RM's in Region A are about 200 rad m^{-2}. This constrains the product

$$n(e)BL = 1.23E-3\ RM$$

where n(e) is the electron density in cm^{-3}, B is the line-of-sight component of the magnetic field in μG, and L is the extent of the plasma along the line of sight in kpc.

Some marginally interesting additional information is available from one pulsar that lies at a high enough latitude to help constrain the picture, although only weakly. PSR 2154+40, at (l,b)=(91°,-11°), has RM=-44 rad m^{-2} and DM=71 cm^{-3} pc (Taylor and Manchester, 1975). This corresponds to a magnetic field strength, computed in the usual naive manner from the ratio RM/DM, of 0.7 μG. However, with an RM of -44 rad m^{-2}, this pulsar samples only about 25% of the total RM of region A. Thus the derived field strength need not characterize the full extent of Region A. Furthermore, its

DM implies a distance of about 2 kpc if the electron density is equal to its usual value of 0.03 cm^{-3}. However, this distance might well be misleading, because at the relatively low latitude of 11° there might be an intervening HII region along the line of sight--and, indeed, from the map of diffuse Hα of Reynolds, Roesler, and Scherb (1974), there does appear to be enhanced Hα emission in this direction. It is more likely that the pulsar lies closer than 2 kpc and that the true magnetic field strength in Region A is higher than 0.7 μG.

Diffuse Hα emission has been surveyed with very high sensitivity on a rough grid of 5 or 10 degrees by Reynolds et al (1974). The intensity of Hα emission increases towards the Galactic plane, where ordinary HII regions exist in abundance. Further from the plane, at latitudes below -20°, the Hα emission is weak, corresponding to EM's smaller than about 7 cm^{-6} pc except for one position near longitude 120°; and at latitudes below -30°, the EM is smaller than 4 cm^{-6} pc. These EM's assume a temperature of 6000 K. A somewhat lower upper limit, for that temperature, of 1.8 cm^{-6} pc is derived by Simard-Normandin and Kronberg from the low-frequency radio data of Novaco and Brown (1978). Upper limits for Hα emission scale roughly $T^{-0.75}$, while upper limits for low-frequency free-free absorption of radio emission scales as $T^{-1.35}$. We will be interested in gas at higher temperatures than 6000 K, so we should use the EM limit derived from Hα Thus, the EM of 4 or somewhat less constrains the product

$$n(e)^2 \ (T/10000\ K)^{-0.75}\ L = 1.47E-3\ EM$$

Measurements of Zeeman splitting of the 21-cm line in emission (Heiles, 1984), made in the directions of many of the same extragalactic sources used in the RM study, show very weak fields in the HI gas, typically no more than a few μG. All of the detected fields point in the same direction as the field that produces the RM's. Nevertheless, the magnetoactive plasma cannot reside in the HI clouds, because then the EM would far exceed the above limit. Thus the HI measurements provide no directly relevant information about the magnetic field in the plasma. However, it seems reasonable to assume that the magnetic field strength in the less dense plasma is no larger than that in the denser HI clouds.

3. DERIVED CHARACTERISTICS

Given the above observational constraints, together with an assumption concerning the ratio of magnetic energy to thermal energy, we can derive the properties of the plasma as a function of a single parameter, which we choose to be L. We assume that the energy ratio is equal to R. It is presumably difficult to obtain R>1, because then the magnetic field would be dominant. However, it is difficult to obtain large RM's unless R is large. So it seems likely that R is roughly equal to unity.

Putting all of the above together with a little algebra, we derive the following:

$$n=1.08\mathrm{E}{-2}\ \mathrm{RM}^{6/17}\ \mathrm{EM}^{4/17}\ R^{-3/17}\ L^{-10/17}$$

$$B=1.14\mathrm{E}{-1}\ \mathrm{RM}^{11/17}\ \mathrm{EM}^{-4}\text{Å}^{17}\ R^{3/17}\ L^{-7/17}$$

$$T=3.44\mathrm{E}{+2}\ \mathrm{RM}^{16/17}\ \mathrm{EM}^{-12/17}\ R^{-8/17}\ L^{-4/17}$$

For the observed values, which we take as RM=200 rad m^{-2} and EM=4 cm^{-6} pc, for an assumed value R=1, and L=1 kpc, we obtain the following:

$$n=0.097\ \mathrm{cm}^{-3}$$

$$B=2.5\ \mu\mathrm{G}$$

$$T=19000\ \mathrm{K}$$

Since the adopted EM might be larger than that characterizing the magnetoactive region alone, the true density might be lower, and the magnetic field and temperature higher, than the values quoted above.

These values don't seem particularly unreasonable from an a priori standpoint. They are quite reasonable in that the pressure nT is about 2000 cm^{-3} K, which is close to the standard interstellar pressure. Over a region 1 kpc in diameter, one expects this criterion to be satisfied.

However, they are unreasonable in an important way. The cooling time scale for such gas is only 5000 years. Such a short cooling time for a diffuse gas occuping such a large volume is unacceptable. Instead, there would need to be an efficient heating source to keep the gas so hot. It is interesting to note that this temperature is just below that where collisional excitation of heavy elements, not just hydrogen, starts to become effective (see, e.g., Dalgarno and McCray, 1972), so it could be an equilibrium temperature if a suitable heating source were available.

It would be more comfortable, however, for the gas to a bit cooler than 10000 K, where the cooling rate rises suddenly with temperature by a factor of about 40 for a fully ionized gas having a normal heavy element content. However, this requires a very large region, because the derived temperature varies slowly with L. A temperature of 10000 K requires that the product R^2L = 15 kpc. Presumably, R < 1, which means L > 15 kpc! This size is reminiscent of a Galactic halo, which hardly falls within the domain of this conference! Nevertheless, we pursue this possibility briefly. The density and magnetic field strength would be 0.020 cm^{-3} and 0.83 μG, respectively. The recombination time scale would be very short, about 4E6 yr, and a source of ionization would be required. It would be surprising for such a region to lie near the outer periphery of the Galaxy unless its primary association was not with our Galaxy. In this context, it is curious that the general direction of this region is the same as that of the most of the galaxies in the local group, including M31 (!). None of all this is totally impossible, we supppose, but in the absence of compelling reasons we prefer to drop this possibility.

Alternatively, if we consider smaller values of L, then the density, magnetic field strength, and temperature all increase. The cooling time scale decreases, both because of the increased density and temperature, and the requirement for a heating mechanism is accentuated. Roughly speaking, the cooling time varies a $L^{0.65}$. Furthermore, the temperature increases above the possible natural equilibrium value caused by heavy element excitation. These factors require a powerful heating mechanism, and it seems preferable for such a heating mechanism to occupy a small, rather than a large, volume of space. A small value of L, e.g. 10 pc, gives n=1.5 cm^{-3}, B=17 μG, and T=56000 K. This field strength is much stronger than that observed in HI clouds in this region. Furthermore, such a strong field strength is encountered only rarely in interstellar space, and then only in relatively dense clouds near regions of star formation. It would be remarkable for such a region to extend over a steradian of sky. Finally, we note that PSR2154+40, mentioned above, has an RM just 25% that of region A. If L were small, it would be improbable for this pulsar to be located within the magnetoactive region.

In the absence of further information it is impossible to make definitive statements about the physical conditions in this region. However, we believe that our arguments above are reasonable, and that without further information we should accept them.

4. DISCUSSION

We conclude that the magnetoactive plasma in Region A probably occupies a very large volume of space and that its properties are roughly as given above for the L = 1 kpc case. The main problem with this possibility is the short cooling time scale for the gas. A pervasive heating mechanism is required to keep the gas at its temperature of about 20000 K.

Two possibilities suggest themselves. One is heating by cosmic rays. Region A lies within the nonthermal radio continuum feature known as Loop II (Berkhuijsen, Haslam, and Salter, 1971). The origin of Radio Loop II is unknown. However, a similar feature, Loop I (also known as the North Polar Spur), was caused by stellar winds and superovae and is filled with hot gas and, probably, cosmic rays (see Heiles et al, 1980). It is reasonable that Loop II and Loop I have similar origins, although Loop II is probably older because it is weaker. Energetically, this picture is attractive because Region A contains about 3E51 erg in thermal energy, close to that expected inside an old shell formed by a collection of supernova and stellar winds. Thus an excess of cosmic rays might well exist inside Loop II, and this could be the heating agent for the gas. Alternatively, but very improbably because of time scale considerations, the gas could be cooling from the original very hot temperature that it had when the Loop was younger.

A less likely possibility is that the plasma is produced and heated by infalling very high velocity gas. The tip of the Magellanic Stream descends into the Galaxy near (l,b) = (90°,-40°) and seems to break up into a multitude of very high negative velocity clouds (Giovanelli, 1981; Mirabel, 1981; Cohen, 1982a,b). It seems quite likely that this disturbance could produce heating of a diffuse ionized gas, perhaps by generating magnetoacousic disurbances. In this case we would expect abnormal velocities of HI clouds because recombination and cooling times are short, However, these are not observed, which seems to be a strong argument against this possibility.

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