COOL IONIZED GAS IN GALAXY THICK DISKS

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ABSTRACT. Spiral galaxies whose radio continuum emission is dominated by their disks show a flattening of the radio continuum spectrum at frequencies well below 1 GHz. The effect appears to be stronger for edge-on than for face-on galaxies The most feasible explanation appears to be that the flattening reflects free-free absorption of nonthermal emission by a very low temperature ionized gas. This gas is probably highly clumped, and must be well-mixed with the nonthermally emitting plasma.

1. Radio Continuum Spectra.

For a long time, reliable radio continuum data at frequencies below 400 MHz, or indeed below 1 GHz have been lacking for most normal galaxies. This spectral region is now becoming accessible. With the presently defunct Clark Lake Radio Observatory 68 galaxies were detected at 57.5 MHz (Israel and Maloney, 1990), while the Cambridge array has been used to observe galaxies at 151 (6C) and 38 MHz. A priori, one might expect radio continuum spectra to steepen at lower frequencies: in composite spectra such as those of galaxies, the steepest spectral component dominates at the lowest frequencies. Thus, thermal emission becomes negligible below 1 GHz, whereas steep-spectrum haloes should become dominant. In fact, the opposite is observed: below a few hundred MHz, the continuum spectra of many, but not all galaxies flatten noticeably. This was already noticed by others, see for instance Slee (1972) and Lerche and Schlickeiser (1982). Few, if any, galaxies exhibit a steepening.

An accurate determination of galaxy radio continuum spectra is not easy. In principle, single dish observations as well as interferometer (aperture synthesis) observations should yield reliable flux-densities. However, at high frequencies (> 5 GHz) galaxy angular extent and low surface brightness tend to conspire to yield integrated flux-densi-

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ties that underestimate the true values. At low frequencies, especially single dishes have large beamsizes that may lead to flux-densities higher than actual by the inadvertent inclusion of unrelated strong background sources. These problems are not insurmountable, but in using data from the published literature, great care must be taken to avoid unreliable or erroneous determinations that unfortunately abound.

2. The CLRO Survey.

In 42 fields, 133 galaxies were surveyed, yielding 68 detections. The majority of nondetections refers to galaxies weak at any frequency. Slightly over half the detected galaxies have also reasonable flux-determinations in the GHz range. Eighteen of these are spiral galaxies without significant central emission at least at 1.4 GHz. For all galaxies, the high-frequency spectrum was extrapolated to the observing frequency of 57.5 MHz and compared with the actually measured value. As usually 1.4 and 5 GHz measurements are the most reliable, these measurements were used to define the high-frequency spectrum. On average, only about two-thirds of the extrapolated flux was detected, with little difference between disk-dominated galaxies and those with significant central emission. This is an upper limit, because the 1 - 5 GHz spectrum was extrapolated without taking into account possible, indeed probable, steepening below 1 GHz due to the decreasing influence of flat-spectrum thermal components and the increasing influence of steep-spectrum nonthermal components.

A plot of the ratio of observed over extrapolated 57.5 MHz flux-densities versus optical axial ratio (a measure for galaxy inclination) revealed for the disk-dominated galaxies a correlation between flux discrepancy and inclination not shared by galaxies with significant (1.4 GHz) central emission. Although determinations for individual galaxies have large possible errors, the relation for the disk-dominated sample appears well-established, in the sense that edge-on galaxies appear to emit a smaller fraction of the expected flux density than face-on galaxies.

For the Local Group galaxy M33 we determined not only the 57.5 MHz flux density, but also fluxes at four other frequencies between 20 and 75 MHz, as well as new flux densities at 151, 327 and 610 MHz (Israel, Maloney & Howarth, 1990, submitted to A&A). M33 is an extended galaxy of rather low surface brightness, so that a reliable spectrum is hard to construct (cf. section 1). The Bonn telescope single dish maps by Buczilowski (1988) in the range 840 to 4750 MHz define a steep high-frequency spectrum with a spectral index α = -0.9 and a spectral break to α = -0.1 around 800 MHz. A less extreme case may be argued in which the high-frequency spectral index is of order α = -0.6 and a spectral break to α = -0.1 is introduced at 300 MHz. The presence of a spectral break is unmistakeable, and the magnitude of the break (range α = 0.8 to 0.5) as well as its location (range 300 - 800 MHz) can be determined by verifying published integrated flux-densities at specifically 600 MHz, or 5 GHz and higher (cf. Israel, Mahoney and Howarth, 1990).

3. Galactic Winds versus Free-free Absorption.

In principle, breaks in galactic radio continuum spectra can be caused by a variety of mechanisms. In practice, limited magnetic field strengths and radio surface brightness of galactic disks reduce the number of possible explanations. If galaxies produce winds perpendicular to the plane, a spectral break of magnitude α = 0.5 occurs at a critical frequency below 1 GHz if the convection-deceleration 'halo' model applies; no such break occurs in static 'halo' models (Lerche and Schlickeiser, 1982). Thus, if M33 indeed has a relatively moderate spectral index of about α = -0.6, the low frequency data are consistent with a galactic wind and a convection-decelaration halo. However, if the Bonn data are correct, the change in spectral index (α = 0.8) appears to large for such an explanation.

Also, the apparent relation between inclination and the ratio of observed to expected flux density of disk-dominated galaxies is not a feature predicted by the galactic wind model. An intriguing alternative explantion is that at low frequencies, the nonthermal emission is absorbed by a thermal plasma (Israel and Maloney, 1990). The observations, in conjunction with known properties of spiral galaxies then place limits on the physical condition of both the thermal and nonthermal components. Efficient free-free absorption at the observed frequencies can only take place if the absorbing gas has a low electron temperature. Absorption by normal HII regions can be ruled out completely. If the thermal absorber is an extended, diffuse gas, constraints on the available ionizing power and on the Hα brightness of the gas lead to electron temperatures of less than a few hundred K, and probably 100 K or less.

If the absorbing thermal gas is very clumpy, electron temperatures may be as high as 500 - 1500 K without exceeding the constraints. Clump volume filling factors should be of order 10^{-3}, and clump densities should be in the range 0.1 - 2.0 cm^{-3}. Emission from such a cold ionized gas at higher frequencies is negligible. Both the small observed to expected flux density ratio and the shape of the M33 low frequency spectrum imply that the absorbing thermal gas must be well-mixed with the nonthermal emitting plasma. This condition is naturally met if the interstellar medium is characterized by a range of clump sizes and densities maintained for instance by compressing shock waves.

It is important to note that in the free-free absorption interpretation the absorbing **must** fill a large fraction (> 60%) of nonthermally emitting plasma, and the absorbing gas **must** have a low electron temperature, independent of the actual detailed geometry.

4. Comparison with the Galaxy.

At present, there is no clearcut Galactic evidence for a similar low electron temperature component in the Galaxy. The lowest electron temperatures inferred for HII regions in the inner Galaxy are of order 3000 K. In a few directions, the presence of a diffuse, local ionized gas with $500 \text{ K} < T_e < 3000 \text{ K}$ has been inferred from H166α recombination lines (Lockman, 1980), but generally it appears that a cold ionized component is not present in the Solar Neighbourhood. An extended diffuse component appears to be absent in the plane of the Galaxy, but a highly clumped, cool ionized component would not contradict the low frequency SNR absorption measurements by Dulk and Slee (1975). It would be interesting to determine the spectral index distribution of the Galaxy in the 50 - 400 MHz range, in particular in the anticentre, centre and polar directions. It should be noted that even if the cool ionized gas is absent in the thin disk (Galactic plane), it still can be a major component of the thick disk, which at 408 MHz contributes 90% of the total flux density of the Galaxy (see Beuermann et al, 1985).

The inclination-dependence of the observed to expected flux ratio, and the magnitude of the spectral break in the M33 spectrum favour the free-free absorption interpretation, and argue against the convection-decelaration halo interpretation. If these arguments were to disappear, both explanations would be a priori equally probable, and independent evidence for or against either galactic winds or cool ionized gas would have to decide the issue.

References.

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