Part 6

Spectral Studies of our Galaxy

The Universe at Low Radio Frequencies
IAU Symposium, Vol. 199, 2002
A. Pramesh Rao, G. Swarup and Gopal-Krishna, eds.

Low frequency Recombination Lines of Hydrogen

K. R. Anantharamaiah

Raman Research Institute, Bangalore, India

Abstract. A brief review of Galactic and extragalactic recombination lines of hydrogen at frequencies ≤ 1.4 GHz is presented.

1. Introduction

Radio recombination lines (RRLs) are useful probes of ionized regions in the Galaxy and in external galaxies. RRLs corresponding to transitions from different quantum levels occur over the entire radio frequency range; e.g. for n=350, ν = 150 MHz and for n = 30, ν = 230 GHz. For the purpose of this review, we will take low frequencies to be $\nu \leq 1.4$ GHz (i.e. $n > 165$). Low frequency RRLs are preferentially detected from lower density ionized gas ($n_e <$ a few hundred cm^{-3}). From higher density gas, RRLs are virtually undetectable at low frequencies because of a combination of effects due to continuum opacity, pressure broadening, and small angular diameter of sources relative to the telescope beams. To date, RRLs below 1 GHz have been detected only from Galactic ionized regions. Surveys of RRL emission from the Galactic plane have been made at 327 MHz (Anantharamaiah 1985, Roshi and Anantharamaiah 2000) and at 1.4 GHz (Lockman 1976, 1980, Hart & Pedlar 1976, Cersosimo 1990 and Heiles, Reach & Koo 1996). RRLs from a number of individual Galactic HII regions and also from partially ionized regions surrounding some of them have been observed near 1.4 GHz (Pankonin et al. 1977, Roelfsema and Goss 1991, Onello and Phillips 1995, Kantharia, Anantharamaiah & Goss 1998). RRLs from two external galaxies, M 82 and NGC 253, have been detected near 1.4 GHz (Roelfsema and Goss 1987, Anantharamaiah & Goss 1990).

2. Expected Intensity Vs. Frequency of RRLs

A key parameter that determines the intensity of RRLs at a given frequency ν is the line optical depth $\tau_{L\nu}$ which is a function mainly of the density (n_e) and the temperature (T_e) of the ionized region and the path-length through the gas. For most interstellar conditions, non-LTE effects invert the high$-n$ level populations which make the optical depth of RRLs negative and produce stimulated emission (Salem & Brocklehurst 1979). Fig 1 shows that non-LTE effects introduce a pronounced dependence of line optical depth on electron density, especially at low frequencies, whereas LTE optical depths are practically independent of density. The reduction in peak LTE optical depth with increasing density seen at low frequencies in Fig 1 is due to the onset of pressure broadening. However, integrated LTE optical depths ($\int \tau_{L\nu}\, d\nu$) remain constant with density. The significant enhancement of peak negative optical depths of RRLs from low-density gas increases their detectability at low frequencies through stimulated emission.

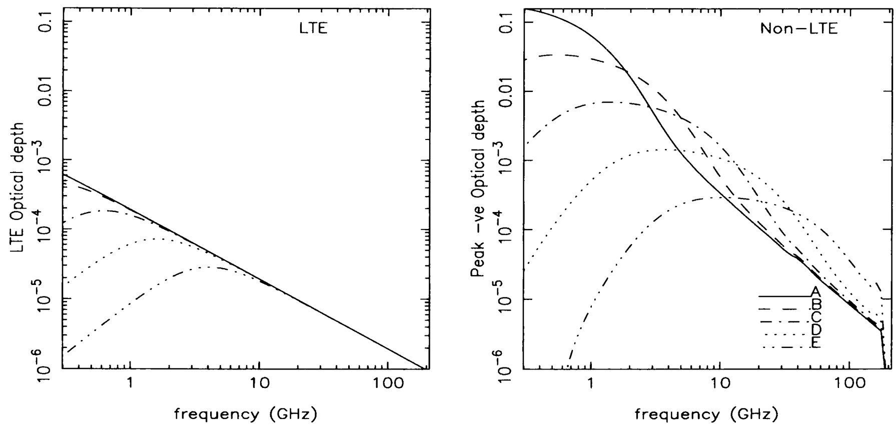

Figure 1. Expected optical depth ($\tau_{L\nu}$) of RRLs under (a) LTE and (b) non-LTE conditions for densities 10^0 – 10^4 cm^{-3} in factors of 10 from A to E. For all the curves T_e = 10^4 K, EM = 10^5 pc cm^{-6} and Δ $V = 30$ km s^{-1}

Fig 2a shows the expected brightness temperature of RRLs from a variety of ionized regions. Chosen parameters range over four orders of magnitude representing compact HII regions (n_e = 10^4 cm^{-3}, L = 0.1 pc) to diffuse ionized gas of the ISM (n_e = 1 cm^{-3}, L = 500 pc). Fig 2 shows that for densities below 100 cm^{-3}, RRLs are more favorably detectable at lower frequencies ($\nu <$ 1 GHz). Furthermore, since lower density gases are typically of larger angular size, they are better matched to observations at low frequencies which typically have larger telescope beams. The sharp increase in the line strength at low frequencies for the lowest density gas (solid and dashed lines in Fig 2) is due to stimulated emission induced by the Galactic non-thermal background.

Fig 2b shows the line strength in units of flux density (i.e. integrated over the angular extent of the source). This observable quantity increases with frequency for all the combination of n_e and L except for the lowest density and at the lowest frequency (solid line). Care should be taken in interpreting the curves in Fig 2b since the angular size of the highest density gas (curve E) is only 4″ whereas that of the lowest density gas (curve A) is 5.7° (i.e. a difference of $\sim 10^7$ in solid angle).

Another point of interest is the suitability of interferometric arrays such as the GMRT or the VLA versus single dishes for observations of RRLs at low frequencies. Since the response of these interferometric arrays diminish rapidly for structures of the order of, or larger than the primary beam ($\sim$ 20′ – 30′ at 1.4 GHz), RRLs from Galactic low-density regions which may have angular sizes $>$ 1° (Roshi and Anantharamaiah 2000) are practically unobservable. On the other hand such large regions are good targets for observations with single dish telescopes. Interferometric arrays would be more suitable for observing RRLs

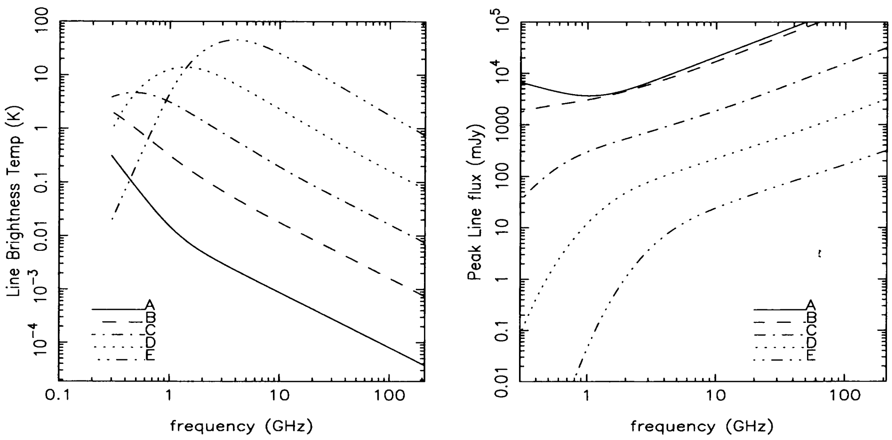

Figure 2. Expected (a) brightness temperature and (b) flux density of RRLs from ionized gas with various combination of density and size. Parameters for the curves from A to E in (cm^{-3}, pc) are (1, 500), (10, 100), (100, 10), (10^3, 1) (10^4, 0.1). For all the curves $T_e = 10^4$ K and $d = 5$ kpc. Stimulated emission due to a Galactic non-thermal background with $T_B = 5000$ K at 100 MHz and $\alpha = -2.6$ is included.

from smaller diameter (and therefore higher density) regions or for observation of stimulated emission in low-density gas against bright background sources of small angular size.

3. Galactic Low frequency RRLs

The first detection of low frequency ($\nu < 1$ GHz) RRLs of hydrogen was towards the Galactic centre by Casse and Shaver (1977) at a frequency of 242 MHz (H300α). Further observations towards the Galactic centre were made near 327 MHz by Pedlar et al (1978), Anantharamaiah & Bhattacharya (1986) and Roshi and Anantharamaiah (1997). The lowest frequency hydrogen RRL detected so far is near 145 MHz (H356α) by Anantharamaiah, Payne and Bhattacharya (1990) towards the Galactic centre. Fig 3 shows RRLs of hydrogen near 1.4 GHz and 327 MHz observed recently in this direction by Anantharamaiah, Pedlar and Goss (1999) using the VLA. The difference in the two line profiles in Fig 3 illustrates that RRLs at different frequencies are sensitive to ionized gas at different densities. While the lower frequency line (327 MHz), which is narrow in width, arises from low-density ($n_e \sim 10$ cm^{-3}) ionized gas which lies somewhere along the line of sight to the Galactic centre, the higher frequency (1.4 GHz) RRL, which is broad, arises in higher density ($n_e \sim 100$ cm^{-3}) gas close to the centre of the Galaxy where the velocity spread is much larger. In fact, Anatharamaiah et al (1999) show that the RRL at 1.4 GHz arises from a more extended ionized component not observed at frequencies above 5 GHz.

RRLs at 1.4 GHz and 327 MHz have been detected at almost all the observed positions in the Galactic plane in the longitude range $l = -10°$ to $80°$

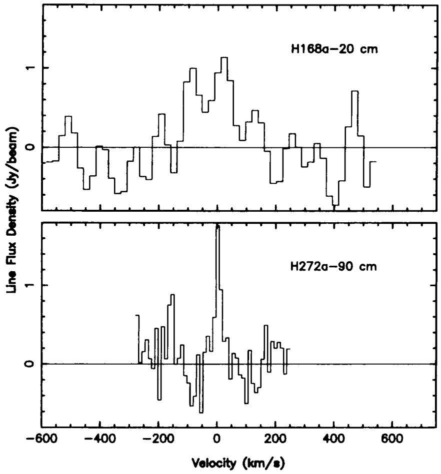

Figure 3. Hydrogen RRL at 1.4 GHz (top) and near 327 (bottom) observed towards the Galactic centre by Anantharamaiah, Pedlar & Goss (1999).

(Heiles, Reach & Koo 1996, Roshi and Anantharamaiah 2000). Except towards the Galactic centre, the line profiles at 1.4 GHz and 327 MHz are similar suggesting that the RRLs at the two frequencies may arise in the same gas. Fig 4 shows a selection of spectra near 327 MHz. Since the telescope beams used for these observations are large ($\sim 2°$), the ionized regions are of large angular size compared to known HII regions in the Galactic plane. From the observed and expected line strengths, it has been shown that these RRLs do not originate in known HII regions. These line arise in a lower density gas which is distributed similar to the HII regions in the Galactic plane. Since non-LTE effects produce significant dependence of the line optical depth on density (Fig 1), it is possible to reliably estimate the density the gas if RRLs at two or more low frequencies is observed from the same gas. Fig 5 illustrates this point for one direction in the Galactic plane from which RRLs at 327 MHz and 1.4 GHz have been observed. Regardless of the temperature, the two sets of EM vs n_e curves in Fig 5 intersect at $n_e \sim 4$ cm^{-3}. Such an analysis of the low frequency RRL data has shown that ionized gas with densities in the range 1-10 cm^{-3} and line-of-sight extent of 20-200 pc occurs in every direction in the inner Galactic plane (Anantharamaiah 1986, Roshi and Anantharamaiah 2000). Roshi and Anantharamaiah (2000) have argued that these ionized regions are most likely the outer low-density envelopes of known HII regions, although the possibility that they represent a population of evolved low-density HII regions is not ruled out.

Another interesting Galactic low frequency RRL of hydrogen is the narrow ($\Delta V \sim 5 - 8$ km s^{-1}) line detected near 1.4 GHz from partially ionized region (H^0 region) surrounding well known HII regions such as W3, Orion B, W48 etc. These narrow lines normally accompany a broad ($\Delta V \sim 30$ km s^{-1}) line from the hot HII region as well as a narrow carbon line which possibly originates in the same partially ionized region as the H^0 line. Observations of such lines have been made using both single-dishes (Pankonin, Thomasson & Barshun

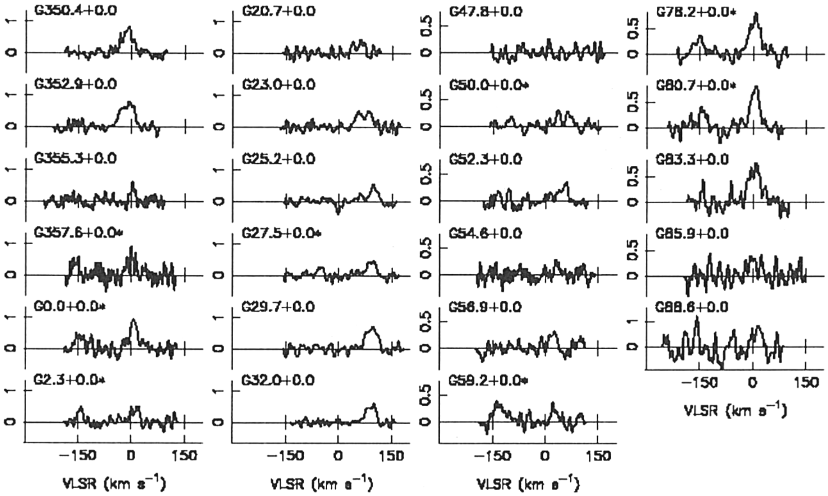

Figure 4. RRLs near 327 at various positions in the Galactic plane observed by Roshi & Anantharamaiah (2000) with a beam of 2°.

1977, Onello & Phillips 1995) and interferometric arrays (Roelfsema & Goss 1991, Kantharia, Anantharamaiah & Goss 1998). These observations provide important information about the density, temperature and ionization structure surrounding the HII regions.

4. Low frequency RRLs from External Galaxies

The lowest frequency at which RRLs have been detected from external galaxies is ~ 1.4 GHz. Only two objects, M 82 and NGC 253 (both starburst galaxies) have been detected in the H166α line (Shaver et al 1977, Roelfsema 1987, Anantharamaiah & Goss 1990). In both the cases, the observed RRL arises in the nuclear starburst region. Although RRLs at higher frequencies (mainly at $\nu \sim 8$ GHz) have been detected in a number of starburst galaxies (Anantharamaiah et al 1993, Zhao et al 1996), searches for lines at 1.4 GHz in some of these galaxies have yielded only upper limits (Anantharamaiah et al 2000, Mohan, Anantharamaiah & Goss 2000). The non-detection of the lower frequency line sets an upper limit to the amount of low-density ionized gas in these starburst regions.

In both M82 and NGC 253, the observed RRL at 1.4 GHz arises in relatively low-density ($n_e < 1000$ cm^{-3}) gas. Stimulated emission due to external non-thermal background radiation is the main contributor to the observed line intensity. Detailed modeling in the case of NGC 253 shows that the higher frequency ($\nu > 8$ GHz) RRLs arise in a higher density gas. Fig 6a shows a two-component model fit to the RRLs observed towards NGC 253. The high density gas (component A1 in Fig 6a) makes negligible contribution to the RRL observed at 1.4 GHz. Conversely, the lower-density gas (component A2 in Fig

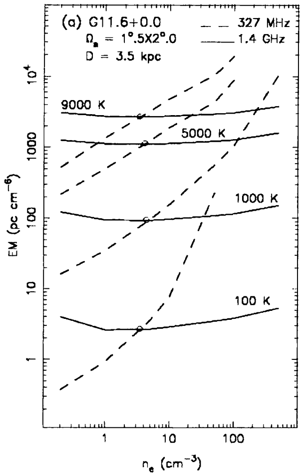

Figure 5. Determination of density using observations of RRLs at 327 MHz and 1.4 GHz. The solid and dashed lines give the required combination of EM and n_e, at different temperatures, to produce the observed RRLs at 1.4 GHz and 327 MHz respectively. The intersection point gives the density.

6a) is not detected in RRLs at higher frequencies. Thus, multi-frequency RRL observations are essential to determine the various components of ionized gas.

In the ultra-luminous infrared galaxy, Arp 220, search for RRLs at 1.4 GHz has yielded a sensitive upper limit ($S_L < 0.25$ mJy, Anantharamaiah et al 2000), although RRLs at a number of higher frequencies have been detected. Modeling showed (see Fig 6b) that two different components of ionized gas are required to explain the RRL observed at $\nu = 8.2$ GHz and at $\nu > 100$ GHz respectively. Neither of these components produce detectable RRLs at $\nu < 1.4$ GHz.

A promising case for detecting low frequency RRLs is stimulated emission in foreground low-density ionized gas along the line of sight to strong background extragalactic objects. As shown in Fig 1, peak negative line optical depths $\sim 10^{-3}$ or higher is possible at $\nu < 1.4$ GHz. Since the detectability will only depend on the strength of the background source and is indepedent of distance, this method offers the possibility of studying RRLs at high redshifts. Background sources could be radio-loud quasars or distant active galactic nuclei. The foreground ionized gas may be in the host galaxy itself or in an intervening system (e.g. a galaxy or a damped Lyman alpha system). Although several searches for such lines have been conducted, no detection has yet been made. The first detailed search was made by Churchwell and Shaver (1978) at 1.4 GHz and 430 MHz towards a number of bright quasars and AGNs using the Arecibo telescope. They obtained upper limits to the optical depth in the range $1 - 4 \times 10^{-3}$. A recent search using the VLA at 1.4 GHz towards seven bright compact sources by Nath, Anantharamaiah and Srianand (2000, in preparation) also yielded similar upper limits. A sensitive search at 1.4 GHz using the VLA towards the gravitational lens system PKS 1830-210 (Mohan, Anantharamaiah

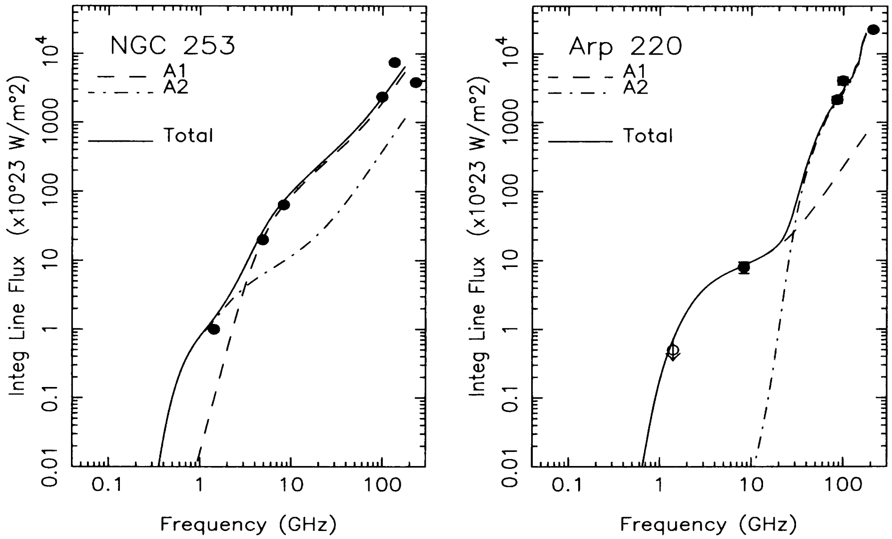

Figure 6. Multi-component models of ionized gas fitted to multi-frequency RRLs observed towards (a) NGC 253 and (b) Arp 220.

and Goss, this volume) and towards B0218+357 using the WSRT (de Bruyn and Chengalur, Private communication) have also resulted in upper limits.

5. Outlook for Future Observations

There are still a number of areas where further observations of low frequency RRLs of hydrogen will be useful. Low-density ionized gas in the Galactic plane observed in RRLs at 327 MHz and 1.4 GHz seem to extend to higher latitudes. Single dish surveys above and below the Galactic plane are required to study this gas. Although low frequency turnover in the continuum spectra of SNRs is thought to be due to the same low-density ionized gas, a direct connection needs to be established through interferometric imaging of stimulated emission of RRL in front of bright SNRs. Such observations at more than one low frequency can be used to reliably determine the density of the gas as well as its spatial structure. Detection of similar low-density gas in external galaxies can be attempted either through interferometric observations of stimulated emission against the central continuum source (especially in edge-on galaxies) or through single-dish observations of nearby galaxies with angular size comparable to the telescope beam. A sensitive search is yet to be conducted at a frequency of $\sim$ 150 MHz for RRLs from the warm ionized medium of the Galaxy. A detection will yield parameters such as the filling factor and temperature of this component of the ISM (Anantharamaiah et al 1990). Further observations of the combination of narrow and broad hydrogen lines near 1.4 GHz due to the partially ionized medium surrounding the HII regions should be conducted with sensitive arrays such as the GMRT. Such observations should also be extended to lower frequencies. More sensitive observations at $\nu \leq 1.4$ GHz are needed to detect and study low-density ionized gas which is known to exist in nuclei of starburst galaxies as seen in NGC 253 and M82. Models indicate that an increase in sensitivity by a factor of 2-3 will be sufficient to detect lines at 1.4 GHz from a number of starburst galaxies. Finally attempts must be continued to detect stimulated emission of recombination lines at low frequencies against bright, distant objects in the universe to study the ionized gas in intervening systems.

References

Anantharamaiah, K.R. 1985, J.Ap.Astr, 6, 177

Anantharamaiah, K.R. & Bhattacharya, D. 1986, J.Ap.Astr. 7, 141

Anantharamaiah, K.R. & Goss, W.M. 1990, in Radio Recombination Lines: 25 years of investigation (Dordrecht: Kluwer), ed. M.A. Gordon & R.L. Sorochenko, 267

Anantharamaiah, K.R., Payne, H.E. & Bhattacharya, D. 1990 in Radio Recombination Lines: 25 years of investigation (Dordrecht: Kluwer), ed. M.A. Gordon & R.L. Sorochenko, 259

Anantharamaiah, K.R., Zhao, J.H., Goss, W.M. & Viallefond, F. 1993, ApJ, 419, 585

Anantharamaiah K.R., Pedlar, A. & Goss, W.M. 1999 in The Central Parsecs of the Galaxy (San Francisco: ASP), ed. H. Falcke, A. Cotera, W.J. Duschl, F. Melia & M.J. Rieke, 422

Anantharamaiah, K.R., Viallefond, F., Mohan, N.R., Goss, W.M. & Zhao, J.H. 2000, ApJ, (July 10 issue)

Casse, J.L. & Shaver, P.A. 1977, A&A, 61, 805

Cersosimo, J.C. 1990, ApJ, 349, 67

Churchwell, E. & Shaver, P.A. 1979, A&A, 77, 316

Hart, L. & Pedlar, A. 1976, MNRAS, 176, 547

Heiles, C., Reach, W.T. & Koo, B.C. 1996, ApJ, 466, 191

Kantharia, N.G., Anantharamaiah, K.R. & Goss, W.M. 1998, ApJ, 504, 375

Lockman, F.J. 1976, ApJ, 209, 42

Mohan N.R., Anantharamaiah, K.R. & Goss, W.M. 2000, (this volume)

Onello, J.S. & Phillips, J.A. 1995, ApJ, 448, 727

Pankonin, V., Thomasson, P. & Barshun, J. 1977, A&A, 54, 335

Pedlar,A., Davies, R.D., Hart, L. & Shaver, P.A. 1978, MNRAS, 182, 473

Roelfsema, P.R. 1987, Ph.D. thesis, Univ. of Groningen, Netherlands

Roelfsema, P.R. & Goss, W.M. 1991, A&AS, 87, 177

Roshi, D.A. & Anantharamaiah, K.R. 2000, ApJ(in press)

Roshi, D.A. & Anantharamaiah, K.R. 1997, MNRAS, 292, 68

Salem, M. & Brocklehurst, M. 1979, ApJS, 39, 633

Shaver, P.A., Churchwell, E. & Rots, A.H. 1977, A&A, 55, 435

Zhao, J.H., Anantharamaiah, K.R., Goss, W.M. & Viallefond, F. 1996, ApJ, 472, 54