Radio Recombination Lines: The Early Years

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Earliest Considerations

- Van de Hulst, H. C. 1945, Nederladsch, Tidjschrift voor Naturkunde, 11, 230
  - predicted that high n H transitions would scale with the f-f continuum emission
  - but are unlikely to be detected because
    - Line widths would be greater that the line separation (Inglis-Teller relation)
    - And, they would be intrinsically weak.
- Reber & Greenstein 1947, Observatory , 67, 15 said they were not of interest because they were too weak to detect.
- Wild, J. P. 1952, ApJ, 115, 206
  - Considered possible H line emission transitions under IS conditions and concluded
    - That only the HI 21 cm line is likely to be detectable in the ISM
    - In fact, as far as I can tell from this paper, he didn't even consider RRLs

Prognosis for IS H Line Emission

1952, ApJ, 115, 206

THE RADIO-FREQUENCY LINE SPECTRUM OF ATOMIC HYDROGEN AND ITS APPLICATIONS IN ASTRONOMY

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Received September 8, 1951

ABSTRACT

Formulae are obtained for the frequencies, transition probabilities, and natural widths of the discrete lines of atomic hydrogen that fall within the radio spectrum. Such lines are due to transitions within either the fine structure or the hyperfine structure of the energy levels.

The conditions necessary for the formation of observable emission and absorption lines are examined. Thence an inquiry is made into which of the hydrogen lines are likely to be observable from astronomical systems. It is found that the sun may give a detectable absorption line at about 10,000 Mc/sec, corresponding to the $2^2S_{1/2}-2^2P_{3/2}$ fine-structure transition, but that other solar lines are not likely to be observable. From the interstellar gas, the emission line already observed (i.e., the 1420 Mc/sec hyperfine-structure line) is probably the only detectable hydrogen line. The importance of this line in the study of the interstellar gas is discussed. Some general conclusions are drawn from the preliminary evidence regarding the motion and kinetic temperature of the regions of un-ionized hydrogen. The ratio data are used to obtain a measure of the product of "galactic thickness" and average hydrogen concentration.

The Key Paper

- Kardashev, N. S. 1959, Astron. Zh. 36, No. 5, 813.
  - Concluded that RRLs should scale with the f-f continuum (as did van de Hulst)
  - They should be strong enough to be detected with radio telescopes at that time
  - They should not be smeared out by either Doppler or Stark broadening to the extend that they would blend with the f-f continuum
  - He over-estimated Stark broadening, but still concluded that it is not critically important at frequencies >7 GHz.
  - This paper, more than any other, encouraged observers to try to detect RRLs

Initial Searches

- The earliest searches, as far as I can make out, were by Russian radio astronomers, probably because they were ware of Kardashev's work. Two groups were involved: Puschino and Pulkovo Observatories.
- At Pulkovo:
  - Egorova & Ryzkov (1960) searched for the H271α line. Not detected.
  - Dravskikh & Dravskikh 1964 searched for the H104α line. Parijskij persuaded them to publish, although they believed the S/N was too low to convince anyone.
  - Dravskikh et al. 1964, Dok. Akad. Nauk SSSR, 163, 332 reported detection of the H104α line with better S/N (within a month of the Puschino detection of the H90α line).

First “Detection”

Dravskikh, Z. V. & Dravskikh, A. F. 1964, Astron. Tsirk,282, 2.

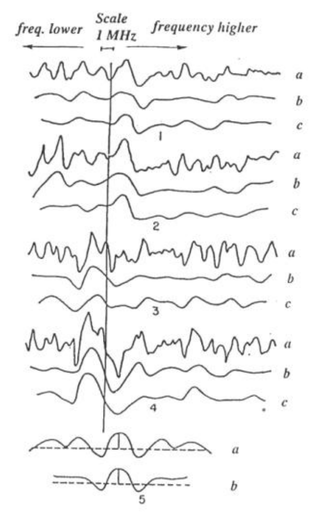


Figure 1.3: Fig.1-5 of Dravskikh and Dravskikh (1964). Fig.1a: Average of the eight spectra of the Omega Nebula at 5.7 GHz, 1b.previous spectrum convolved with a 1 MHz filter, 1c. a different smoothing scheme; Fig.2: same as Fig.1, but only 4 spectra of the Omega Nebula, Fig.3: Average of all five spectra of Orion. Fig.4: Average of only three spectrograms from Orion, Fig.5: The average of the left and right sides of the spectra (centered about the line proposed position) in the Omega (a) and Orion (b) nebulae. The vertical line marks the radial velocity position of 0 km s^{-1} with respect to the Local Standard of Rest (LSR) for the $n_{105} \rightarrow n_{104}$ line.

H104α

Russian Detections Continued

- Lebedev Physical Institute (Puschino Observatory)
  - Sorochenko & Borodzich 1965, Dokl. Akad. Nauk. SSSR, 163, 603 reported detection of the H90α line with good S/N toward M17 on Apr. 27, 1964.
- Both the Puschino and Pulkovo detections were reported at the XII IAU GA in Hamburg, Germany on 31 Aug. 1964 (the official date of the detection of RRLs according to Sorochenko).

Sorochenko & Borodzich (1964) detections

Test

M17

Earth Rot.

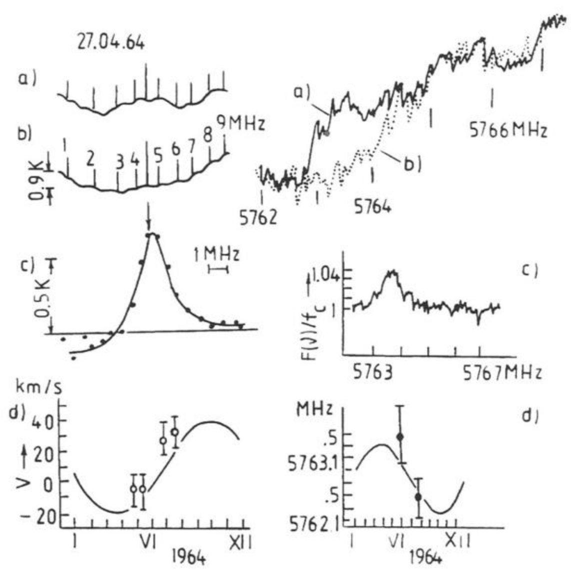


Figure 1.5: The first spectrograms of excited hydrogen lines with good signal-to-noise ratios that were presented to the IAU General Assembly in Hamburg, Germany, in 1964.

Orion

Germany/US Searches

- Mezger and co-workers at Stockert Telescope (25m) in Germany attempted to detect the H132α line in 1960 after seeing Kardashev's paper. Unsuccessful. Not enough sensitivity and spectrometer probably not adequate.
- Tried again in Fall of 1964 using the 85ft antenna of NRAO at Greenbank, W Va. Again unsuccessful probably because receiver was too unstable.
- Hoglund & Mezger in 1965 using the new 140 ft telescope detected the H109α line toward M17 and Orion with high S/N, but not Cyg A or Tau A.
- Lilley et al from Harvard detected the H156α and H158α lines toward M17 and W51 within days of hearing of Hoglund and Mezger's detections.

Hoglund&Mezger 1965 Detections

Hoglund, B., Mezger, P. G. 1965, Science, 150, 339

Note S/N, non-detection toward nonthermal sources Cyg A and Tau A. Detections, 9 July 1965

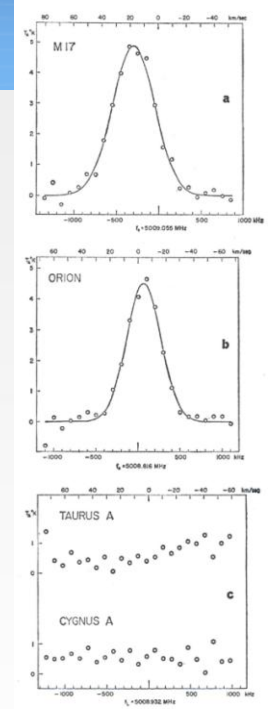


Fig. 2. *a*, Line profile of M 17; f_0 is the theoretical line frequency reduced to the local standard rest. The frequency and velocity scales are given with respect to LSR. Line temperature is given in units of antenna temperature. Integration time is 42 minutes. *b*, Line profile of the Orion nebula. Integration time is 133 minutes. *c*, Line profiles of Taurus A and Cygnus A. Integration times, 35 and 133 minutes, respectively. The frequency and velocity scales are given with respect to the theoretical line frequency (f_L).

Australians

- Bolton, Gardner, & Robinson searched for the H109α line with the Parks Telescope (64m), but missed the line due to the narrow bandpass of the receiver and an inaccurate approximation of the line frequency. Bad luck.

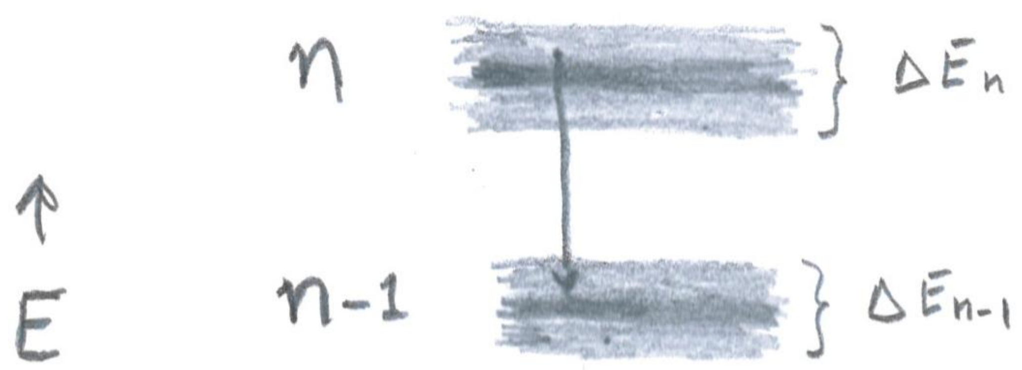
The Line Broadening Problem

- All theories of RRLs predict substantial Stark (pressure) broadening in typical HII regions, especially for transitions involving principal quantum levels greater than n~100
- But observations of transitions with n~100 or greater showed very little evidence for broadening greater that that attributable to thermal and turbulent motions.

Line Broadening Continued

- Key papers:
  - Kardashev (1959)
  - H. R. Griem 1967, ApJ, 148, 547
  - Minaeva, Sobelman, & Sorochenko 1967, Astron. Zh., 44, 995
  - Brocklehurst & Seaton 1972, MNRAS, 157, 179
- Resolution (2 effects)
  - Both Griem and Minaeva et al. found that adjacent levels at high n in Hydrogenic atoms are perturbed by nearby electrons by about the same amount, which results in very little change in line frequency and line FWHM. High electron densities and large n transitions are pressure broadened and produce Voigt profiles in which most of the pressure broadening occurs in Lorentzian wings, but the central profile is only weakly affected. Broad wings are particularly difficult to detect.
  - Brocklehurst & Seaton argued that typical HII regions have a range of electron densities and RRLs are generally most heavily weighted by the lowest density gas that also occupies the largest volume which produces the least pressure broadening.

Schematic of Energy Levels



$$\Delta E_n = f(\text{natural, thermal, turb, pressure})$$

Departures from LTE

- Key Paper: Goldberg, L. 1966, ApJ, 144, 1225
- The problem: In the absence of stimulated emission, the line-to-continuum ratio $I_L/I_C = (\Delta\nu\ T_L)/T_C = (\tau_L^*/\tau_C)\ e^{-\tau}$ which is inversely proportional to the electron temperature to the -1.15 power. But electron temperatures derived from the line-to-continuum ratios were systematically lower than electron temperatures derived by other methods.
- The solution: Goldberg showed that Rydberg state n is slightly over-populated relative to n-1, and n-1 is over-populated relative to n-2, and so on. Stimulated emission is a natural consequence of this, resulting in brighter lines relative to the continuum and an apparent electron temperature lower than the kinetic temperature of the electrons.

b_n vs n

b_n <1 for lower n orbitals

b_n increases with n mostly due to collisions with electrons

b_n is a function of T_e and n_e

Corrections for stimulated emission => more accurate estimates for T_e and n_e

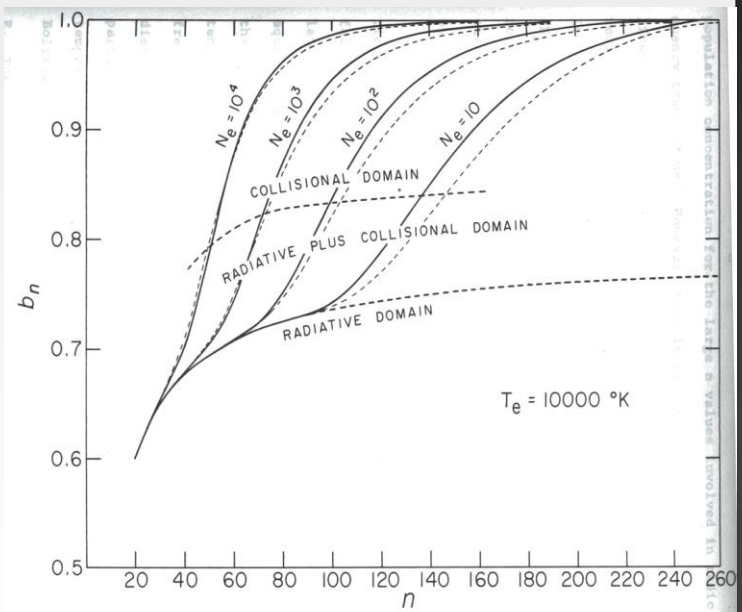


Figure II.4 b_n vs n for T_e = 10 000 °K and $10 \le N_e \le 10^4$ cm^{-3} after Sejnowski and Hjellming (1969). The approximate collisional, collisional plus radiative, and radiative domains are indicated.

Example of Current Standards

Quireza et al. 2006, ApJS, 165, 338

Note: H & He lines all have the same velocity, but C lines are different.