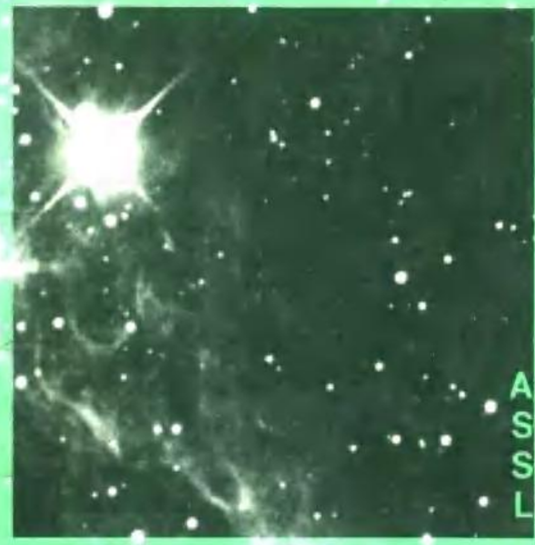
Radio Recombination Lines: 25 Years of Investigation

M. A. Gordon
R. L. Sorochenko
(editors)



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RADIO RECOMBINATION LINES: 25 YEARS OF INVESTIGATION

PROCEEDINGS OF THE 125TH COLLOQUIUM OF THE INTERNATIONAL ASTRONOMICAL UNION, HELD IN PUSCHINO, U.S.S.R., SEPTEMBER 11–16, 1989

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KLUWER ACADEMIC PUBLISHERS

DORDRECHT / BOSTON / LONDON

Library of Congress Cataloging in Publication Data

International Astronomical Union. Colloquium (125th : 1989 :
Pushchino, Moscow, R.S.F.S.R.)
Radio recombination lines : 25 years of investigation :
proceedings of the 125th Colloquium of the International
Astronomical Union, held in Puschino, U.S.S.R., September 11-16,
1989 / edited by M.A. Gordon, R.L. Sorochenko.
p. cm. -- (Astrophysics and space science library ; v. 163)
Includes bibliographical references and indexes.
ISBN 0-7923-0804-2 (U.S. : alk. paper)
1. Radio recombination lines--Congresses. I. Gordon, M. A. (Mark
A.), 1937- . II. Sorochenko, R. L. III. Title. IV. Series.
QB462.5.I56 1989
522'.682--dc20 90-4713

ISBN 0-7923-0804-2

Published by Kluwer Academic Publishers,
P.O. Box 17, 3300 AA Dordrecht, The Netherlands.

Kluwer Academic Publishers incorporates
the publishing programmes of
D. Reidel, Martinus Nijhoff, Dr W. Junk and MTP Press.

Sold and distributed in the U.S.A. and Canada
by Kluwer Academic Publishers,
101 Philip Drive, Norwell, MA 02061, U.S.A.

In all other countries, sold and distributed
by Kluwer Academic Publishers Group,
P.O. Box 322, 3300 AH Dordrecht, The Netherlands.

Printed on acid-free paper

Printed in the Netherlands

FOREWORD

The year 1989 was the 25th anniversary of the astronomical detection of radio lines from highly excited atoms. In the years following, these lines—known as Radio Recombination Lines (RRLs)—have become a powerful tool to astronomers for distinguishing thermal sources from nonthermal ones, for studying star formation regions, for investigating the diffuse interstellar medium, and for exploring galactic structure.

This book contains the proceedings of the IAU Colloquium 125, focussed on the 25 years of astronomical research with RRLs since their discovery in 1965. The colloquium was held on September 12–14, 1990 in Puschino, USSR—a research station of the USSR Academy of Sciences located about 100 km south of Moscow on the banks of the Oka river.

For many of us this was an historic occasion. First, it was an opportunity to meet people whom we had come to know only by name in the scientific literature. Second, it was an opportunity to appreciate the enormous scope of RRL astronomical research over the last 25 years. And, third, it was an opportunity to remind ourselves that RRL research also involves research into the fundamental physics of atoms and not just astronomy.

The Colloquium covered a wide range of topics. This book contains papers dealing with research into Rydberg atoms both in the laboratory and in the interstellar medium of our galaxy and others. It contains papers dealing with the interaction of radiation and atomic systems, as well as with the effects of inadiabatic collisons between these atoms and both ions and electrons. It deals with astronomical observations of atoms with "diameters" ranging from $0.08\mu m$ to $50\mu m$—a factor of 625 in size. It deals with RRLs in absorption, in emission, and as true masers. And, it deals with plasmas with temperatures ranging from 10 to greater than 10^4 Kelvins, and with an even larger range of volume densities.

Although in some respects a sequel to the Ottawa Workshop on RRLs held on August 24–25, 1979, this meeting involved a much larger number of people representing many countries. Additionally, it dealt with the exciting new topics of low frequency RRLs discovered in 1980 and of the maser RRLs from the star MWC349 discovered in 1989. The advent of aperture synthesis telescopes and large single-element telescopes are now making possible RRL studies with high angular resolution, studies which will enhance the wonderful results already in hand. Our hope is that the papers in this volume will serve as a platform from which to search new horizons in RRL research.

For this meeting the Scientific Organizing Committee consisted of K. R. Anantharamaiah (India), J. Caswell (Australia), M. A. Gordon (USA), W. M. Goss (USA), D. Hoang-Binh (France), P. G. Mezger (FRG), P. A. Shaver (FRG), and R. L. Sorochenko (USSR). Shaver and Sorochenko served as Co-Chairmen.

We thank the Scientific Organizing Committee and the meeting participants for an excellent program, the Local Organizing Committee for a well-organized meeting, Jolanda Karada of Kluwer Academic Publishers for help with publication, and the USSR Academy of Sciences and the International Astronomical Union for their financial support.

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POSTULATION, DETECTION AND OBSERVATIONS OF RADIO RECOMBINATION LINES (REVIEW)

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ABSTRACT. Radio recombination lines (RRL) detected 25 years ago are [illegible] investigated in a wide, from mm to dam, range of wavelengths It has [illegible] cleared out that in Galaxy conditions an atom as a quantum system may exist with excitation level n of up to 1000 reaching the giant size of 0.1mm. RRL proved to be a new powerful tool for astrophysical research.

1. PREDICTION AND DETECTION OF RADIO RECOMBINATION LINES

Atomic spectral radiation caused by transitions between levels with different principal quantum numbers (n) was detected about 100 years ago. The lines were the well known Lyman, Balmer and Paschen line series emitted by hydrogen in UV, visible and IR ranges. From this observations Bohr (1913) developed his quantum theory of atom, in which the spectral lines' frequencies are defined by

$$\nu = R\ (1/n_1^2 - 1/n_2^2) \cong 2R\ \Delta n/n^3 \ \text{(if } n \gg 1) \qquad (1)$$

where n_2 and n_1 - are the principal quantum numbers of upper and lower levels respectively, $\Delta n = n_2 - n_1$, and R is Rydberg's constant (for hydrogen $R = 3.288057 * 10^{15}$ Hz).

Bohr's theory explained the observed series as transitions to the first three atomic levels ($n_1 = 1,2,3$), and it predicted new lines. Although it did not restrict the number of atomic levels nor [illegible] number of line series, the theory gave no indication of how many serie could be detected in practice. Progress of experimental studies towards the longer wavelength was very slow. The fourth series, the Bracket series ($\lambda_{5-4} = 4.05\mu m$) was detected nine years after Bohr's theory had appeared; the fifth series, the Pfundt ($\lambda_{6-5} = 7.46\mu m$) after 11 years; and the sixth with $\lambda_{7-6} = 12.3\ \mu m$, only after 40 years, as a result of minute spectrum measurements of gas discharge (Humphfrey, 1953).

With these measurements the classical laboratory spectroscopy ran out of abilities. Only new research technique could find new series. Here is a situation where astronomy can not only solve a problem in physics but gain a new field of astronomical research at the same time.

M. A. Gordon and R. L. Sorochenko (eds.), Radio Recombination Lines: 25 Years of Investigation, 1–17.

Van de Hulst (1945) was the first to note the possibility of radioline radiation from transitions between highly excited levels of atoms in the ISM. In his classical paper, where the 21cm line was predicted, Van de Hulst also considered radiation from ionized hydrogen for both free-free and bound-bound transitions. The expressions he obtained for the integrated intensity and the Doppler broadening of the radio lines well agree with modern concepts. But, Van de Hulst estimated the Stark broadening incorrectly and, as a result, he concluded that excited hydrogen radio lines (EHRR) were too dispersed and were therefore unobservable. For the same reasons, Wild (1952) later came to the same pessimistic conclusion.

In 1959 Kardashev came to the opposite conclusion. Independantly from Van de Hulst* he had made calculations of EHRR intensity and linewidth, and deduced that in HII regions such lines maybe detectable. He showed that n,n-1 transitions would be the most probable and the resulting radio lines are observable by normal radioastronomical techniques (Kardashev, 1959). Kardashev's prediction drew attention of radioastronomers in many countries and stimulated subsequent experimental and theoretical investigations into EHRR.

The first attempt to detect EHRR was undertaken in Pulkovo by Egorova and Ryzkov (1960). They searched for the hydrogen radio line $n_{272}-n_{271}$ (λ=91.2cm) in the Galactic plane, l_1=60°-115°, but did not detect it. Additional theoretical calculations made it possible to define the intensity of expected radio lines more accurately and thereby optimise a search in wavelength and sources (Sorochenko, 1965). Fig.1 shows the result of these calculations. In the mm range where the linewidth is defined only by Doppler broadening $T_L \sim \lambda$. In the cm range T_L reaches a maximum and then begins to drop, with increasing n because of Stark broadening. This calculations include worked out by Griem (1960) theory of spectral line broadening in plasmas. Detection of the expected radio lines was determined to be most probable in cm range at λ=2-5 cm in the bright and spatially extendeded HII regions, the Omega and Orion nebulae.

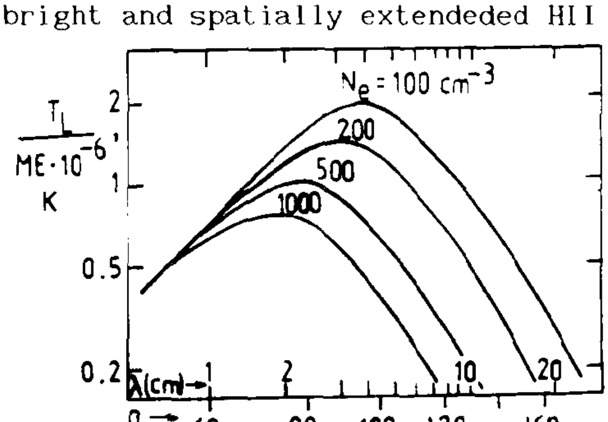

Fig.1 Brightness temperature in line's centre normalised by emission measure as a function of wavelength, level number n and HII electron density.

In April 1964, at a wavelength of 3.38cm and with the 22-m radiotelescope of Lebedev Physical institute in Pushchino, Sorochenko and Borodzich (1965) detected the excited hydrogen radio line n=91-90 (ν=8872.5

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* Van de Hulst's paper was published in 1945 in very rare edition which was absent from soviet libraries. It became known considerably later in USSR in english edition (Sullivan, 1982).

MHz) in the spectrum of the Omega nebula. The line was distinctly seen even in single spectrograms. Observations carried out in the next three months showed the Doppler shift of line frequency to agree with the orbital Earth rotation and proved conclusively the cosmic origin of the line.

In the same time the Pulkovo Observatory resumed it's attempts to detect the EHRR. Their search was conducted in the range of 5cm. The initial attempts undertaken in December 1963 appeared to have detected

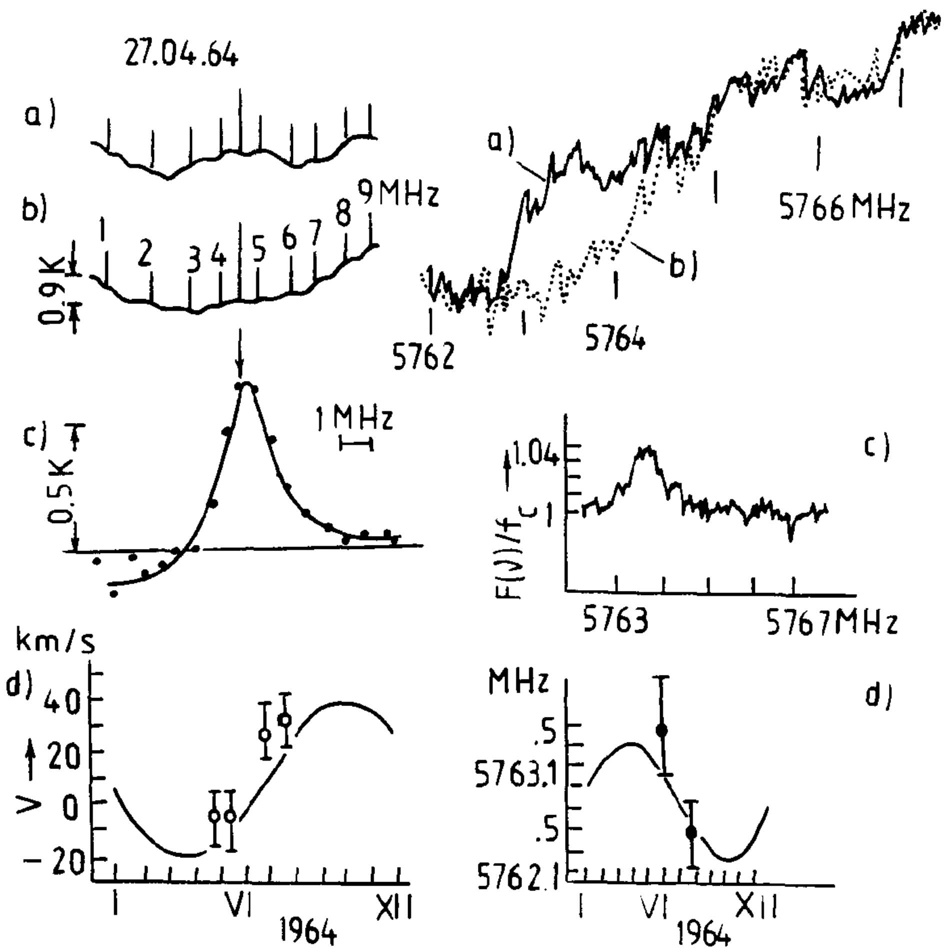

Fig. 2 First spectrograms of excited hydrogen radiolines and the observed radial velocity (frequency) shift due to Earth rotation.

On the left, Pushchino H90α line observations. a) Omega nebula's spectrogram. b) test spectrogram for antenna off the source; c) averaged result of seven measurements towards Omega and five test measurements made on April 1964. The abscissa is frequency, the ordinate is the antenna temperature, big mark is calculated line frequency and the vertical dashes are of 1MHz; d) measured Doppler shift during the year 1964. The curve indicates the nebulae's calculated radial veloc. relative to Earth.

On the right, Pulkovo observations of *H104α* a) spectrogram towards Omega; b) test spectrogram; c) averaged 12 spectrograms obtained in May 1964. The abscissa is the frequency, the ordinate is the ratio of nebula's spectral to continuum flux densities; d) measured Doppler shift during the year 1964. The curve shows the calculated frequency shift.

the line n=105-104 at the frequency of 5763MHz (λ=5.21cm) (Dravskikh and Dravskikh, 1964). In May-June of 1964 the hydrogen radio line n=105 104 was definitely detected in Omega nebula following improvements to the equipment which increasing it's sensitivity (Dravskikh et al,, 1965).

The first spectrograms of the excited hydrogen lines H90α* or H104α which were detected with a high signal/noise ratio, obtained in the Lebedev Physical Institute and in Pulkovo, are given in Fig.2.

Both soviet groups reported the discovery of exited hydrogen radio lines at the 12th IAU Gen. Assembly on 31 of August 1964 (Dravskikh, Dravskikh and Kolbasov; Sorochenko and Borodzich,1964) 25 years ago!

In July of 1965 Höglund and Mezger (1965) detected H109α radio line in Orion, Omega and 9 other HII regions with the 42-m radiotelescope of National Radioastronomical Observatory. By the end of 1965 Lilley et al. (1966a) of Harvard detected two more lines H156α and H158α in the range of 18cm. Soon, EHRR observations were expanded to the wavelength of 75cm, when the H253α line was detected by Penfield, Palmer and Zuckerman (1967); the H104α line was detected in 8 sources (Gudnov and Sorochenko, 1967) and the H109α line, in 16 (Mezger and Hoglund, 1967).

In 1966 Lilley et al. (1966b) reported detection of three exited helium radio lines He156α, He158α and He159α in Omega. The possibility of helium radio lines detection had also been predicted by Kardashev(1959). In 1967 Palmer et al. (1967) detected a radio line with frequency a bit higher than the He109α frequency in NGC 2024 and IC 1795. Goldberg and Dupree (1967) identified this line as radiation from excited carbon C109α line. Fig.3 shows the IC1795 spectrum with hydrogen, helium and the new lines.

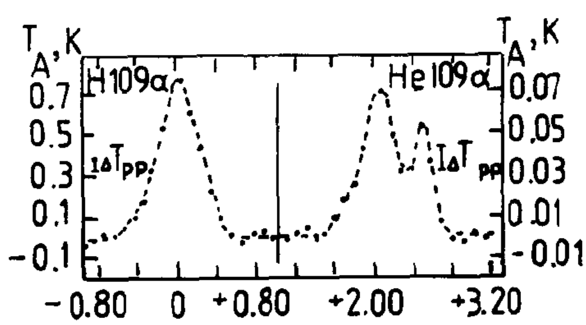

Fig.3 Spectrum of the source 1795 with H109α, He109α lines and new one later identified as C109α. The abscissa is the frequency relative to the rest frequency H109α (MHz) (Palmer et al., 1967).

These obsevations gave impetus to broad research into excited atomic radio lines or radio recombination lines (RRLs) as they were called because the emission is preceded by the recombination process.

2. RRLs: NEW RESULTS IN ATOMIC PHYSICS.

2.1. Stark Broadening.

The first observations of excited hydrogen radio lines showed that the line has no broadening and disperse as a function of n as was expected from the theory (Sorochenko and Borodzich, 1965; Hoglund and Mezger,

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*Here and farther on we use the adopted convention for highly exited radio lines: the element's name by Mendeleev's table, the principal quantum number of the lower level, line's order (by Greek letters)

1965; Lilley et al.,1966a). All the observed RRLs up to n=158 showed pure Doppler broadening. The failure to detect Stark effects contradicted both Kardashev's early estimations of the broadening and the later more rigorous theory by Griem (1960) which formed the basis for the width and intensity calculations of EHRR (Sorochenko, 1965).

New theoretical consideration (Griem, 1967; Minaeva, Sobelman and Sorochenko, 1967) showed that, for an astrophysical plasma with low densities and high velocities of the exciting particles, an impact approximation is the appropriate method to calculate Stark broadening. Here during the elastic interactions between highly excited atoms and charged particles the compensation of Stark effect occures: cl neighbouring levels distort similarly, and their energy difference i changed much less than the energies of the levels themselves. The inelastic interaction dominate the classical elastic ones, thereby reducing the Stark broadening of RRLs.

The revised Stark theory decreased the expected line broadening, and explained the first observational results in Omega nebula But subsequent observations led to new difficulties. Obsevations of the H220α lines in Orion (Pedlar and Davies, 1971) required the nebula's density $N_e < 200 cm^{-3}$. Contrarily the optical observations of forbidden lines gave a density $N_e = 10^4 - 10^5 cm^{-3}$ (Osterbrock and Flatter, 1959). Furthermore, the same high densities were necessary to explain the intensities, of RRLs observed at many different wavelenghts (Sorochenko and Berulis, 1969). To demonstrate this Fig.4 shows all the observation data obtained for Orion up to 1971 and theoretical results expected for different densities.

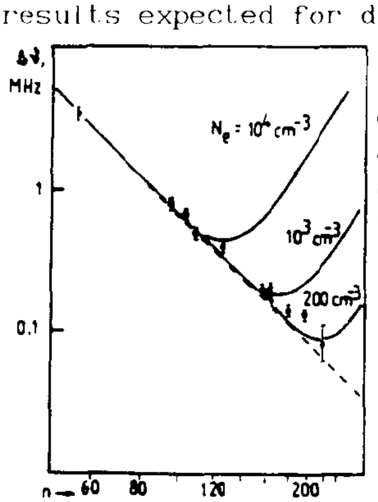

Fig.4 The RRL line width as a function of n in Orion. The dotted line is the Doppler width determined from H56α line. The curves are the calculated values of the line widths due to Stark broadening for different densities N_e.

A number of other experimentors also came to conclusion that the new theory overestimates the Stark broadening. Churchwell (1971) observed linewidths to increase with n, which he explained by Stark broadening, but the broadening's magnitude was substantially less than expected. Davies (1971) concluded that theory evidently overestimated Stark broadening by an order of the value.

The possibility of agreement between theory and experiment arose when the effect of Stark broadening was shown to be considerably decreased by inhomogeneous densities within nebulae (Brocklehurst and Seaton, 1972; Gulyaev and Sorochenko, 1974; Lockman and Brown, 1975).

This hypothesis was confirmed by special Stark broadening observations carried out at two radiotelescopes: 100-m in Effelsberg and 22-m in Pushchino (Smirnov, Sorochenko and Pankonin, 1984). At RT-22 at a wavelength of 8.2mm ($\Delta\varphi_A$=1.9 ang.min.), they precisely measured the H56α line shape towards the central part of Orion nebula from which the Doppler core of the line was determined. In the same direction with the Effelsberg telescope at λ=3.3cm, the lines' profiles of H90α, H114β, H128γ, H141δ, H152ε and H161ζ were measured with the same angular resolutiion as RT-22. Unlike the previous experiments the RRLs were observed from the same volume of gas and comparison of the H56α line unbroadiened because of atom and electron interactions with the lines of higher levels, should permit the separation of Stark and Doppler broadeining.

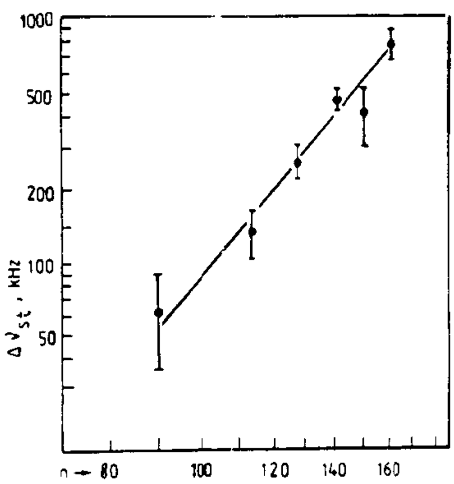

Fig.5 The measured dependence of Stark broadening on level number. The curve is the theoretical dependence $\Delta\nu \sim n^{4.4}$.

Fig.5 shows the results of the measurements. The observed experimental dependence of RRL Stark broadening on level number n well agrees with the revised broadening theory and is quantified (Smirnov, Sorochenko and Pankonin, 1984; Smirnov, 1985) by the relationship:

$$\Delta\nu_{St} = 8.3(n/100)^{4.4}\,N_e\ ,\ \text{Hz} \qquad (2)$$

2.2 Intensity of Radio Recombination Lines. Maser Effect.

In addition to the absense of Stark broadening the RRL data at fir- posed a second problem: the radio lines intensity. Kardash- pioneering work (1959) showed that the ratio of radio line and continuum intensities could be used to determine the electron temperature of HII regions as $(T_L/T_c)\Delta\nu_D \sim T_e^{-1}$ (T_L - line's brightness temperature, T_c - the continuum temperature and $\Delta\nu^L_D$ is the Doppler linewidth).

Even in the first measurements there was a contradiction between the T_e values gained by RRLs and by optical emission. Mezger and Hoglund (1967) obtained an average value of T_e=5820K for the 16 sources observed in H109α line and Dieter (1967) found T_e=5200K by 39 sources in H158α. At the same time by optical measurements of HII regions indicated the temperature of 10,000K.

Goldberg (1966) was the first to suggest that the intensity of RRLs can be essentially dependent on the nonequilibrium of the population of highly exited levels (non-LTE effect). He showed that the line's absorbtion coefficient must be described by:

$$k_L = k_L^* \beta b_n , \quad (3)$$

where $k_L^* = 3.5*10^{-12}(N_i N_e/T_e^{2.5})(f_{n+\Delta n,n}/n)I(\nu)$

is the absorption coefficient of local thermodynamical equilibrium (LTE) population, $f_{n+\Delta n,n}$ is the oscillator's strength (for $\Delta n=1$ $f_{n+1,n}=0.191n$), $I(\nu)$ is the normalized, $\int I(\nu)d\nu$, distribution of spectral density, b_n is the departure coefficient less than one characterising the deviation from LTE of the n-th level, and

$$\beta = [1- (kT/h\nu)(d\ln b_n/dn)\Delta n]$$

is a value which accounts for the decrease of absorption coefficient as a consequence of non-LTE.

From expression (3) it follows that non-LTE effect may considerably change the line absorption coefficient to a vanishingly small or even to a negative value, i.e. there can be an amplification at the line frequency, a "partial maser effect" (Goldberg, 1966). For small optical depths both in the continuum and in the line, i.e., τ_c and $\tau_L \ll 1$ the expression characterising amplification in line is:

$$T_L/T_c = (T_L/T_c)^{LTE} b_n [1+(\tau_c/2)(1-\beta)] \quad (4)$$

where $(T_L/T_c)^{LTE}$ is LTE ratio of the line and continuum temperatures. Because of $T_e \sim (T_L/T_c)^{-1}$ the increase in line intensity causes an underestimation of the T_e values obtained from the RRL observations.

Subsequent theoretical and experimental studies both supported and developed Goldberg's theory. Hjellming and Churchwell (1969), considering the non-LTE effect with departure coefficiens calculated by Sejnovski and Hjellming (1969), obtained T_e=11,000K for Orion. Hjelming and Davies (1970) obtained T_e=10,000K from observations of a series of lines near 6cm (H110α, H138β, H158γ, H173δ and H186ε) from Orion and the number of HII regions. The LTE value of T_e increased with line's order. This result well agreed with the theory according to it the maser amplification effect must decrease as a function of Δn.

New RRL observations in the mm range contradicted this already accepted viewpoint. Sorochenko and Berulis (1969) and Sorochenko et al. (1969) reported H56α observations in the 8.2mm range, where maser effect is negligible and the derived T_e values do not depend on the partial maser effect, obtained T_e=7750±650K for Orion and T_e=7500±1000K for Omega.

The question of interpreting of the RRL observations and obtaining correct values of T_e, for instance, in Orion was the subject of active discussions in the 1970s. Hoang-Binh (1970) noted that the high frequency RRL measurements must give the most precise T_e values because they are only weakly affected by the partial maser effect. Placing great significance upon the high frequency observations, he obtained T_e=8000K for Orion. Gordon (1970) meanwhile, having made observations of H85α, H106β, H121γ and H138δ lines and assigning the highest possible error to the H56α line's observation reaffirmed the T_e=10,000K value for Orion.

Shaver (1970) came to conclusion that maser effect does not have as strong an influence on T_e as suggested by Goldberg (1966); that the increase in line intensity is balanced by Stark broadening and that influence of the optical depth's influence. He found that values of T_e 8000K for Omega and Orion were correct. Nevertheless, still unexplained was the observed decrease of the RRL intensity with line's order. Soon the phenomenon was made clear. It was noted that in the high order lines Stark-broadened wings defined by Voigt line's profile were of great importance (Simpson, 1973; Berulis, Smirnov and Sorochenko, 1975; Shaver and Wilson, 1979). When a baseline selected the wings are partially c , thereby decreasing line intensities. In any given frequency range, this effect increases with the order of the transitions.

The situation with T_e and with RRL intensities respectively was finally cleared up in the last decade as the result of a series of theoretical and experimental work. New calculations using precise cross-sections of atom-electron interaction (Salem and Brocklehurst, 1979; Hoang-Binh, 1983) showed that the population of highly exited levels of hydrogen in HII regions is closer to LTE and that the maser effect is smaller than considered earlier.

Shaver (1980a) deduced that at cm wavelengths in real HII regions there is no essential change in RRL intensities due to non-LTE effects. In the majority of cases the LTE assumption describes the intensity of the RRLs, and therefore T_e, within 10-15%. Also each HII region, depending on, it's emission measure, has an optimal frequency range, $\nu_{opt}=0.081\ EM^{0.36}$, where the maser effect is balanced by Stark broadening and, the optical depth. Because of this T_e definition error can be reduced to 2-3% in this frequency range (Shaver, 1980b). Observations of the H66α line which is situated in optimal frequency range for Orion of ~20GHz yeilded T_e=8200∓300. Observations of the intensity ratio of the H66α and H83β radio lines correspond to the theoretical value with one σ standard definition (Wilson, Bieging and Wilson, 1979).

Now at least for hydrogen all the evidence suggests that the RRL intensity theory is fairly well developed, and that satisfact agreement with experimental data exists over a wide frequency range.

2.3. The Range of RRL Investigations: How Many Distinct Levels are there in an Atom?

The RRL observations started at the range of 3-21 cm and began spreading towards both short and long wavebands. Towards shorter wavelengths, the mm range was important for a number of reasons: 1) negligible RRL Stark broadening, 2) small optical depths of HII regions and the corresponding insignificance of "maser effect" simplifing the observations' interpretation, 3) higher angular resolution for single-dish instruments. Unfortunately in mm range the RRL brightness temperature is smaller, and the equipment's sensitivity is worse than for longer waves.

The first RRL observations in mm range were carried out at 22-m radiotelescope in Pushchino. The H56α radio line (λ=8.2mm) was detected in the Omega nebula (Sorochenko et al., 1969). Soon the RRL observations shifted to the 3.5mm range: the H42α radio line was detected in Orion (Waltman et al., 1973). The shortest RRL wavelength detected at this time H30α (λ=1.3mm), was observed at 30-m radio telescope of IRAM in the CRL 618 source (Martin-Pintado et al., 1988).

The RRL investigation in the mm range helped to tackle the HII region temperature isue (sec. 2.2), to determine the population of the highly exited levels and to find the b_n values. For densities of $N_e=10^2-10^4\ cm^{-3}$ which are usual for HII regions, the collision processes no longer dominate level population for n<60 (λ<1cm). The b_n values noticebly

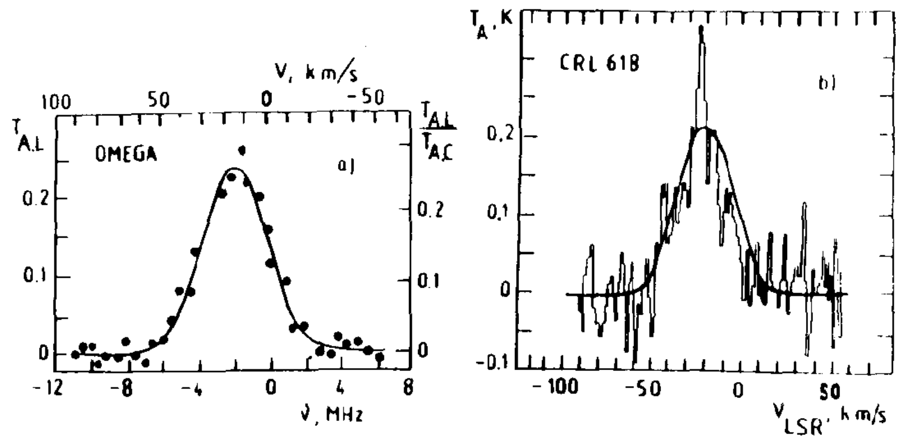

Fig.6 a)H56α line spectrum in Omega nebula (Sorochenko et al., 1969). b)H30α spectrum in CRL618 (Martin-Pintado et al., 1988).

deviate from 1 and we can measure them. The b_n dependence on n was found to be well described by Salem and Brocklehurst's theory (1979) (Sorochenko, Rydbeck and Smirnov, 1988). The RRL research at mm range is detailed inreview by Gordon (present edition).

A very important event was the expansion of RRL investigations to a longer waves. The revised Stark broadening theory showed that the RRL are available at substantially higher atomic levels than assumed before, and the establishment of the quantum number of the limiting levels was extremely important.

The above mentioned early RRL investigations at long wavelengths were limited by a wavelength of 75 cm. The H253α line in prolonged and rarefied North America nebula (W 80) was detected in Jodrell Bank at 76m radiotelescope (Penfield, Palmer and Zuckerman, 1967). However a decade passed before any lower frequency line were detected. The lines: H274α and H275α were detected towards W49 and W51 sources with the 300-m radiotelescope in Aresibo. They were also emitted by low density HII regions (Parrish, Conklin and Pankonin, 1977).

After his theoretical analysis of the population of excited levels Shaver (1975) showed that, at low frequencies in the conditions of the rarified plasma of the ISM, the stimulated emission is important. The ISM amplifies the galactic background radiation and discrete sources at the RRL frequencies, this amplification maybe crucial for the detection of low frequency lines.

Shaver's theoretical calculations were confirmed by subsequent experimental data. H252α line of noticebly greater intensity than expected for LTE was detected towards the galactic centre with the 76-m radiotelescope in Jodrell Bank (Pedlar, Davies and Hart, 1977). Later, also in the direction of the Galactic centre were detected the H271α (λ=91.5cm) and H300α (λ=1.25m) lines (Pedlar et al., 1978). The intensity of both lines were also enhanced by stimulated emission. The good agreement between theory and experiment reqired that the RRLs originate in low densi-