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ON REDSHIFT DETERMINATION FROM RADIO RECOMBINATION LINES

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1. INTRODUCTION

In the optical range many radio galaxies and quasars show emission lines. The redshifts of such objects are determined from measurement of wavelengths of emission lines identified.

The possibility of redshift deriving of radio galaxies and quasars would essentially expand if one could determine the redshift from radio recombination lines of excited hydrogen and other elements.

Osterbrock (1978) described physical conditions dominating in the regions responsible for radio emission lines of galaxies and quasars. The gas in these regions is photoionized by a central source coincident with compact radio nucleus. There can be noted three regions of electron density: the first one with $n_e \geqslant 10^8$ cm^{-3} is concentrated within several parsecs from the central source, the second with $n_e \approx 10^4$-10^6 cm^{-3} has the size of hundred of parsecs, and the third with $n_e \approx 10^3$ cm^{-3} stretches to thousands of parsecs. The three regions have normal abundances, the electron temperatures in all the regions are ~ 15000 K. The second and third regions are of interest in the sense of detection of recombination radio lines.

Shaver (1979), Dravskikh and Parijskij (1981) have reported that such lines can be detected in radio galaxies and quasars. Depending on physical conditions in the ionized regions, whether or not these regions are in the state of local thermodynamic equilibrium (LTE), recombination lines can be observed in absorption or in emission.

The brightness temperature T_l in the lines from radio galaxies and quasars with the central compact nuclear source for optically thin HII regions is equal to

$$T_l \approx -T_0\tau_l,$$

where T_0 is the brightness temperature of the non-thermal nuclear source, τ_l is the line optical depth.

In the case of LTE the line must be observed in absorption. As the deviation from LTE increases, the optical depth first decreases (becomes smaller than τ_l^* at LTE), reaches zero and then becomes negative.

At LTE the ratio of brightness temperatures in the line T_l^* and in the continuum T_{con} is proportional to $\nu^{1.1}$, where ν is the radiation frequency,

$$T_l^*/T_{con} = \tau_l^*/\tau_{con} \propto \nu^{1.1}.$$

If the observed intensity variation of two lines satisfies the law

$$\frac{T_{l1}}{T_{con1}} \Bigg/ \frac{T_{l2}}{T_{con2}} \propto \left(\frac{\nu_1}{\nu_2}\right)^{1.1},$$

then the region HII is in the state of LTE and, using the formulae for LTE, one can compute the electron temperature in the region and other parameters.

In the absence of LTE (Goldberg, 1968)

$$\frac{T_l}{T_{con}} = \frac{T_l^*}{T_{con}}\left[b_n\left(1+\frac{1}{2}\tau_{con}\frac{kT_e}{h\nu}\frac{d\ln b_n}{dn}\Delta n\right)\right],$$

where k is the Boltzman constant, h is the Plank constant, T_e is the electron temperature, Δn is the difference of the numbers of quantum levels of the corresponding lines, b_n is the ratio of the real population to the population at LTE, $d\ln b_n/dn$ is the variation of level populations or the differential deviation from LTE.

At a sufficiently large deviation from LTE

$$\frac{T_l}{T_{con}} \propto \frac{1}{\nu^2},$$

$$\frac{T_{l1}}{T_{con1}} \Bigg/ \frac{T_{l2}}{T_{con2}} \propto \left(\frac{\nu_1}{\nu_2}\right)^{-2}.$$

Thus, observation of several recombination lines of radio galaxies and quasars will permit to draw a conclusion on the conditions in HII regions surrounding the non-thermal source of the synchrotron radiation.

First it seems impossible to define the redshift using recombination radio lines, e.g. hydrogen, since the location of the lines in the spectrum is comb-like, and ambiguity arises in identification of the observed line with the quantum level number responsible for this line. However, in reality it is different. It will be shown below that the redshift of the source can be determined from the measurements of two recombination radio lines.

2. THE METHOD OF REDSHIFT MEASUREMENTS OF A RADIO SOURCE USING RECOMBINATION RADIO LINES

Let us consider the method for hydrogen recombination lines.

The frequency of recombination lines in the coordinate system of the source is defined by the Ridberg formula:

$$\nu=R(n^{-2}-(n+1)^{-2}, \qquad (1)$$

where R is the Ridberg constant, n is the number of the lower of the two excited quantum levels participating in the emission of the given line.

In the observer's coordinate system the line frequency of the source possessing the redshift Z will be

$$\nu_{con}=\frac{\nu}{1+Z}\ . \qquad (2)$$

Observing two neighbouring lines one can derive from (1) and (2) the following equations:

$$\nu_{1con}(1+Z)=R(n^{-2}-(n+1)^{-2}),$$

$$\nu_{2con}(1+Z)=R(n-1)^{-2}-n^{-2}), \qquad (3)$$

where $\nu_{1con,2con}$ are the observed frequencies of two lines, n is the number of the quantum level common for two lines. From the ratio of expressions (3) we obtain

$$\frac{\nu_{1con}}{\nu_{2con}}=\frac{2n^3-3n^2+1}{2n^3+3n^2-1}\ . \qquad (4)$$

Neglecting the unities in the numerator and denominator, we make an error of the order of 10^{-6} (since $n \approx 100$). As a result we obtain

$$n \simeq \frac{3}{2}-\frac{\nu_{2con}+\nu_{1con}}{\nu_{2con}-\nu_{1con}}\ . \qquad (5)$$

The simplifications made and the inevitable final measurement accuracy of line frequencies will lead to a non-integer n. Approximation to the nearest integer is inavoidable. But due to quantification of the solution this circumstance improves the sensitivity and makes it almost absolute, if the errors of n measuring do not exceed 0.5.

Having measured n, we obtain Z from (3). To improve the sensitivity, one should use both equations (3)

$$Z = \frac{R}{2}\left(\frac{n^{-2}-(n+1)^{-2}}{\nu_{1con}} + \frac{(n-1)^{-2}-n^{-2}}{\nu_{2con}}\right)-1. \qquad (6)$$

Z can be measured from any two recombination lines of the given element.

3. THE REDSHIFT MEASURING ACCURACY

The redshift measurement inaccuracy may be due to two reasons. The first one is the measurement error of the number of the quantum level responsible for the line, the second one is the measurement errors of the mean frequency of the observed line profile.

3.1. Measurement errors of the number of the quantum level *n*.

The number of the quantum level the observed line corresponds to is found by expression (5). Hence, taking into account that the measurement errors of the mean frequencies of two observed lines are $\sigma(\nu_{1obs})$ and $\sigma(\nu_{2obs})$ and that they are approximately equal, we derive rms for n measurement

$$\sigma(n) = \pm\, 3\sqrt{2}\; \frac{\nu_{obs}\,\sigma(\nu_{obs})}{(\nu_{2obs}-\nu_{1obs})^2}\,. \qquad (7)$$

The frequency measurement error $\sigma(\nu_{obs})$ is determined by the width of the observed line $\Delta\nu_{obs}$ and by the signal/noise ratio N of the detector

$$\sigma(\nu_{obs}) \approx \frac{\Delta\nu_{obs}}{N}\,. \qquad (8)$$

Then

$$\sigma(n) = \pm\, \frac{3\sqrt{2}}{N}\; \frac{\nu_{obs}\cdot\Delta\nu_{obs}}{(\nu_{2obs}-\nu_{1obs})^2}\,. \qquad (9)$$

As has already been mentioned, the computed value of n (see (5)) is approximated to the nearest integer, and if the error $\sigma(n)$ is less than a half, it means that n is defined absolutely accurately. For example, for the centimeter wavelength range, where $\nu_{con} \approx 10^{10}$ Hz, the line width corresponding to purely thermal motion of particles is $\sim 10^6$ Hz, however, due to turbulent motions with velocities ~200 km/s the line width $\Delta\nu_{con}$ will be $\sim 7\cdot 10^6$ Hz, $\nu_{2con}-\nu_{1con} \approx 3.5\cdot 10^8$ Hz; it is necessary that $N \geq 5$, then n is determined correctly. In observations such a value of N is minimum for any observations to be undertaken at all. Considering on this basis that measurement errors of n are absent, from (6) we will derive the expression for the measurement error of Z:

$$\frac{\sigma(Z)}{1+Z} = \pm \frac{\sigma(\nu_{obs})}{\sqrt{2}\ \nu_{obs}}, \tag{10}$$

or taking into account (8),

$$\frac{\sigma(Z)}{1+Z} = \pm \frac{\Delta\nu}{\sqrt{2}\ N\nu_{obs}}. \tag{11}$$

3.3. Measurement errors of the mean frequency of the observed line profiles

The measurement error of the line frequency is defined by expression (8). The line width is chiefly determined by turbulent velocities in the source, which will introduce the principal measurement error of the mean frequency and therefore of Z.

4. CONCLUSION

Recombination α-lines of excited hydrogen were observed from a number of extragalactic sources. The Table presents a list of such sources. Optical redshifts are presented also. It would be interesting to define radio redshifts of these sources from observations of pairs of recombination α-lines.

But especially interesting for such observations are radio galaxies and quasars whose continuous spectra have a steep slope in the low-frequency part. If this slope is caused by the fact that the synchrotron radiation of a source is absorbed by the ionized gas located around the source, then in this part of the spectrum recombination lines in absorption or in emission may be detected depending on physical conditions in the ionized gas.

Observations of hydrogen recombination lines of extragalactic sources with the aim of studying their radio redshifts demand instruments with effective areas of more than 1000 m^2, low noise level of the system (less than 100 K), and long observing time (hours). To observe two lines simultaneously, it is necessary to use spectrographs overlapping at least double a distance between two neighbouring lines at the frequency of observations. For sources with the unknown redshift this is necessary as the line position is not determined.

Attention should be paid to the fact that the distance between two neighbouring recombination lines shifted towards the frequency of observations due to the redshift increases as $(1+Z)^{1/3}$. And hence it follows that the spectrograph band must be even wider, if we want to detect Z markedly different from zero. The spectrograph band for redshift observations from a simultaneously observed pair of recombination radio lines must be as follows

$$\Delta\nu \geqslant 3.2\cdot10^{-5}\nu_0^{4/3}\ (1+Z)^{1/3}.$$

Finally we present the estimate of Z measurement errors. For the case considered $\nu_{obs} = 10^{10}$ Hz, $\Delta\nu = 7\cdot10^{6}$ Hz, and $N = 6$. From expression (11) we will have

$$\frac{\sigma(Z)}{1+Z} \approx 10^{-4}.$$

This shows that redshift measurements of extragalactic sources from observations of a pair of hydrogen recombination lines are perspective.

Table.

No.	Source	Z_{opt}	Line number n	Flux density in line max. mJy	Line width km/s	References
1	0045-25	0.001	112α	12±1	175±18	Mebold et al.,1980
	(NGC 253)		102α	20±3	309±65	Seaquist & Bell,1977
2	0951+69	0.001	166α	15±2	250±40	Shaver et al.,1977
	(M82)			32±5	338±40	Shaver et al.,1978
			110α	22±2	293±20	Shaver et al.,1978
			102α	21±5	92±30	Bell & Seaquist,1977
			92α	71±10	107±20	Chaisson & Rodrigues,1977
			85α	9±1.5	149±25	Bell & Seaquist, 1978
3	1404+28	0.077	99α	~ 10	-	Bell, 1980
	(OQ208)		83α	~ 10	-	Bell, 1980

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