1968, *Bull. Astr. Inst. Netherlands* **19** 414–416;
Communication from the Astrophysical Laboratory of the Observatory at Utrecht and the Observatory at Leiden

ON THE POSSIBILITY OF AMPLIFICATION OF 21-cm RADIO EMISSION IN HIGH-VELOCITY CLOUDS

H. G. VAN BUEREN and J. H. OORT

Received 24 January 1968

The suggestion by SHKLOVSKY (1967) that 21-cm radiation from high-velocity neutral-hydrogen clouds might be enhanced by a maser effect due to pumping by galactic Lα radiation is critically investigated. An estimate of the Lα radiation intensity is obtained. It is shown that, owing principally to the large optical depth of the moving clouds for this radiation, an inverted population of the ground-state hyperfine structure levels will not occur and amplification of 21-cm radiation will therefore not take place. The same negative conclusion holds for clouds in the galactic plane.

In recent years a considerable amount of data have become available on high-velocity neutral hydrogen at high galactic latitudes (cf. HULSBOSCH and RAIMOND, 1966; OORT, 1966; BLAAUW and TOLBERT, 1966; BLAAUW, FEJES and TOLBERT, 1967; OORT, 1967). This high-velocity gas is moving preponderantly towards the galactic plane; the total flow towards this plane is surprisingly large. Following a theoretical analysis by VARSHALOVICH (1967), SHKLOVSKY (1967) has suggested that the 21-cm radiation from these clouds might have been enhanced by a maser effect due to pumping by Lα radiation from the Galaxy, such that an inverted population of the ground-state hyperfine doublet would occur. Background 21-cm radiation would then be amplified in passing through the cloud, and the observed 21-cm emission intensity of the cloud would be much larger than that corresponding to its thermal radiation. The same effect might, according to FISCHEL and STECHER (1967), occur in low-latitude galactic neutral-hydrogen clouds moving with suitable velocities with respect to Lα-emitting H II regions. Amplification factors ranging between 10 and 100 were in both cases expected. We want to point out that these estimates are much too optimistic.

Consider the balance between the various processes of excitation and de-excitation that determine the populations of the 1 $S_{\frac{1}{2}}$ and the 2 $P_{\frac{1}{2},\frac{3}{2}}$ multiplet levels of hydrogen atoms, occurring in a moving cloud irradiated by (blue-shifted) Lα radiation. From this balance follows the normalized population difference r of the two ground-state hyperfine structure levels 1 $S_{\frac{1}{2}}$ ($F = 1$) and 1 $S_{\frac{1}{2}}$ ($F = 0$) (further to be called a and b, respectively) as

$$r = \frac{n_b/g_b - n_a/g_a}{(n_a + n_b)/(g_a + g_b)} = \tag{1}$$

$$= \frac{J - \dfrac{A_R}{B} - \dfrac{P}{B}\dfrac{h\nu_R}{kT_k}}{J + \dfrac{A_R + B_R R}{B} + \dfrac{P}{B}\left(1 - \dfrac{g_b}{g_a+g_b}\dfrac{h\nu_R}{kT_k}\right) + \dfrac{g_b}{g_a+g_b}\Delta J}\,.$$

Here n_a and n_b denote the level populations, and g_a and g_b the respective statistical weights. A_R and B_R are the Einstein coefficients (in the intensity gauge) for the radio-frequency transition between levels a and b at the frequency $\nu_R = 1.420 \times 10^9$ s^{-1}, and B is an averaged Einstein coefficient for the optical Lα transition. P is the probability per second that an atom will go from state b to state a as a result of a spin-exchange collision with another atom, R is the intensity of the 21-cm line radiation, and T_k is the kinetic temperature of the cloud. J and $J + \Delta J$ are the received Lα intensity at the frequency $\nu_L = 2.47 \times 10^{15}$ s^{-1} corresponding to the 1 $S_{\frac{1}{2}}$ ($F = 1$)$-$2 $P_{\frac{3}{2}}$ transition and this intensity at the slightly higher frequency $\nu_L + \nu_R$ corresponding to the 1 $S_{\frac{1}{2}}$ ($F = 0$)$-$2 $P_{\frac{3}{2}}$ transition, respectively. The galactic Lα emission is considered to have a Doppler-broadened profile with half-width $\Delta\nu_g$, while the cloud absorption occurs in a Doppler-broadened profile with half-width $\Delta\nu_c = 1.2 \times 10^{11}$ s^{-1}, corresponding to an internal velocity dispersion of 10.3 km/sec, as observed in the high-velocity clouds. The centre of this absorption is shifted with respect to that of the galactic emission by an amount ν_V towards longer wavelengths, owing to the radial motion of the cloud with velocity V towards the galactic plane. We have, in good approximation,

$$\frac{\Delta J}{J} = \frac{2\nu_V \, \nu_R}{(\Delta\nu_g)^2}. \tag{2}$$

Inserting the appropriate numerical values $A_R = 2.85 \times 10^{-15}\ \mathrm{s}^{-1}$, $B_R = 0.16\ \mathrm{erg}^{-1} \cdot \mathrm{cm}^2$, $B = 3.0 \times \times 10^{-4}\ \mathrm{erg}^{-1} \cdot \mathrm{cm}^2$ and $P = 5.0 \times 10^{-11}\, n_H T_k{}^{0.23}\ \mathrm{s}^{-1}$, where $n_H = n_a + n_b$, and T_k is taken as 125 °K (PURCELL and FIELD, 1956), we can now express r numerically as a function of J and ΔJ, with R and n_H as parameters. The radio intensity R can be expressed in the observed 21-cm radiation temperature of the cloud T_b as $R = 1.3 \times 10^{-13}\, T_b\ \mathrm{erg} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$.

An estimate of J is obtained by considering the galactic H II regions as the most important sources of Lα radiation. The total Lα emissivity of a typical diffuse emission nebula is estimated as $3 \times 10^{38}\ \mathrm{erg} \cdot \mathrm{s}^{-1}$, of a planetary nebula as $3 \times 10^{36}\ \mathrm{erg} \cdot \mathrm{s}^{-1}$; the total L$\alpha$ intensity of the galactic disk owing to these sources is then $J_0 \approx 1 \times 10^{-4}\ \mathrm{erg} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$. Of this radiation intensity only a fraction of the order

$$J_1 = J_0 \mathrm{e}^{-(\nu_V/\Delta\nu_g)^2} \frac{\Delta\nu_c}{\Delta\nu_g} \tag{3}$$

can be absorbed by the moving cloud. To compute the value of J_1 [and ΔJ_1 with the help of an equation similar to eq. (2)] as a function of the parameters ν_V, that is, of the velocity V, and $\Delta\nu_g$, we considered three cases. In case a) only thermal broadening in the sources at temperature 10^4 °K is taken into account, and $\Delta\nu_g = 1.1 \times 10^{11}\ \mathrm{s}^{-1}$; in case b) also random motions of the Lα sources with a velocity dispersion of 25 km/sec are considered, and $\Delta\nu_g = 3.0 \times 10^{11}\ \mathrm{s}^{-1}$; in case c) the velocity dispersion by galactic rotation is added to the former, and $\Delta\nu_g = 4.6 \times 10^{11}\ \mathrm{s}^{-1}$.

The optical radiation fluxes J_1 and ΔJ_1 thus computed must be considerably reduced before equating them to J and ΔJ occurring in eq. (1), because of two reasons.

1) Absorption.—On its way out of the galactic disk to the high-latitude clouds the Lα radiation encounters neutral H-atoms which scatter it, and dust particles which absorb it. Assuming a mean neutral-hydrogen density of 1 H atom $\cdot\ \mathrm{cm}^{-3}$, a dust-to-gas ratio of 1:100 and a mean dust particle diameter of 6×10^{-5} cm, the effective absorption coefficient is $8 \times 10^{-4}\ \mathrm{pc}^{-1}$. The path length of the Lα quanta might be considerably increased by resonance scattering when they encounter a low-latitude neutral-hydrogen cloud moving with a suitable velocity. (Resonance scattering by atoms at rest will be negligible in the frequency region that is absorbed by fast moving high-latitude clouds.) Under unfavourable circumstances the effective absorption coefficient can be increased by this reason to a value of order $10^{-2}\ \mathrm{pc}^{-1}$, which means that some absorption of the outgoing radiation in the dust layer of thickness about 100 pc will indeed take place. We, therefore, estimate the reduction factor of the Lα intensity owing to absorption to be $0.1 < \alpha < 1$.

2) Optical thickness of the moving cloud.—The theory of amplification by Lα pumping is applicable only if the probability for absorption of the red-wing Lα radiation in the moving cloud is small. Otherwise, owing to resonant scattering in the cloud, the sloping spectrum of the relevant exciting radiation is converted to a thermal profile with positive (spin) temperature related to the kinetic temperature of the cloud (centred around the frequency $\nu_L - \nu_V$) and the population difference r decreases to a correspondingly negative value (WOUTHUIJSEN, 1952). The optical depth of a typical moving cloud as a function of frequency is given by

$$\tau_\nu = \tau_0 \exp\left[-\left(\frac{\nu - \nu_L + \nu_V}{\Delta\nu_c}\right)^2\right] = \tau_0 \exp\left[-\left(\frac{\delta\nu}{\Delta\nu_c}\right)^2\right], \tag{4}$$

where $\tau_0 = 3.4 \times 10^{-14}\, N_H$, if N_H denotes the columnar hydrogen density of the cloud in cm^{-2}. Therefore, at any given moment, only those atoms in the cloud experience the sloping profile, which at that moment absorb at a frequency distant from the line centre by an amount $\delta\nu > \delta\nu_0$, where $\delta\nu_0$ is given by

$$\tau_0 \exp\left[-\left(\frac{\delta\nu_0}{\Delta\nu_c}\right)^2\right] = 1.$$

At every moment the fraction of excitable atoms is clearly

$$f = 1 - \mathrm{erf}\left(\frac{\delta\nu_0}{\Delta\nu_c}\right). \tag{5}$$

In other words, of the incoming radiation only the fraction f is effectively used in the production of an inverted hyperfine doublet population.

Even for the smallest observed values of N_H, viz. $N_H = 5\times10^{18}$ cm^{-2}, corresponding to a brightness temperature $T_b = 0.1$ °K, the reduction factor f is only 10^{-6}; for $T_b = 2$ °K it becomes 10^{-7}. It approaches unity only if $N_H < 10^{14}$ cm^{-2}. Since it can be shown by actual computation [based on eq. (1)] that the amplification factor due to stimulated emission under no conditions exceeds a value of about 30, even by taking such amplification into account clouds which were not to show the effect of optical thickness would have to be thinner by about a factor 1000 than those actually observable.

After inserting the appropriate numbers in eqs. (2) and (3), and multiplying the values of J_1 and ΔJ_1 thus obtained by the product of α and f, we obtain relevant figures J and ΔJ for the final computation of r according to eq. (1). We see from that equation that $r > 0$ only when

$$\alpha f \Delta J_1 > \frac{A_R}{B} + \frac{P}{B}\frac{h\nu_R}{kT_k}. \quad (6)$$

Since the right-hand side of this inequality is at least equal to $A_R/B = 0.95\times10^{-11}$ erg · cm^{-2} · s^{-1}, we see that a positive population difference can only be expected when at least

$$\Delta J_1 > 10^{-5} \text{ erg} \cdot \text{cm}^{-2} \cdot \text{s}^{-1},$$

where for α and f we have taken the largest allowed values 1 and 10^{-6}, respectively. Now this condition can be fulfilled in neither case a), b) nor c). In fact, one finds from eqs. (2) and (3) the following numbers:

Case a) $(\Delta J_1)_{max} = 1.2\times10^{-6}$ erg · cm^{-2} · s^{-1} reached at $V = 9.5$ km/sec.
Case b) $(\Delta J_1)_{max} = 1.7\times10^{-7}$ erg · cm^{-2} · s^{-1} reached at $V = 25.5$ km/sec.
Case c) $(\Delta J_1)_{max} = 5.2\times10^{-8}$ erg · cm^{-2} · s^{-1} reached at $V = 39.0$ km/sec.

Hence, we conclude that, owing principally to the large optical depth of the moving hydrogen clouds for Lα radiation, an inverted population of the ground-state hyperfine structure levels will not occur. The same negative result holds for clouds in the galactic plane, since for them the relevant N_H values are higher than for the high-velocity clouds, and the Lα fluxes in question do not differ appreciably from those we have computed. Actually, they may be even smaller because of more absorption.

We want finally to remark that another result of VARSHALOVICH's (1967) work, viz. that the presence of a *directed* beam of Lα radiation might also produce an inverted population between two of the three magnetic sublevels of the 2 $S_{\frac{1}{2}}$ ($F = 1$) level and the ground-state level, fails to work in actual galactic situations for precisely the same reason. Again, owing to the large optical depth the directivity of the incoming radiation is already destroyed by resonance scattering after it has penetrated only a superficial layer of the cloud.

The authors are indebted to Professor H. C. van de Hulst for valuable discussions.

References

A. BLAAUW and C. R. TOLBERT, 1966, *Bull. Astr. Inst. Netherlands* **18** 405

A. BLAAUW, I. FEJES and C. R. TOLBERT, 1967, *Radio Astronomy and the Galactic System*, ed. H. van Woerden (Academic Press, London, New York) *Symp. I.A.U.* **31** 265

D. FISCHEL and T. P. STECHER, 1967, *Ap. J.* **150** 51

A. N. M. HULSBOSCH and E. RAIMOND, 1966, *Bull. Astr. Inst. Netherlands* **18** 413

J. H. OORT, 1966, *Bull. Astr. Inst. Netherlands* **18** 421

J. H. OORT, 1967, *Radio Astronomy and the Galactic System*, ed. H. van Woerden (Academic Press, London, New York) *Symp. I.A.U.* **31** 279

E. M. PURCELL and G. B. FIELD, 1956, *Ap. J.* **124** 542

I. S. SHKLOVSKY, 1967, *Radio Astronomy and the Galactic System*, ed. H. van Woerden (Academic Press, London, New York) *Symp. I.A.U.* **31** 291. See also *Soviet Astr.* **11** 240

A. VARSHALOVICH, 1967, *Soviet Phys. JETP* **25** 157

S. WOUTHUIJSEN, 1952, *Physica* **18** 75