32. ON THE PHYSICAL CONDITIONS IN INTERSTELLAR H I GAS

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Abstract. Weighted average values of the ionization ratio n_e/n_H for the interstellar gas can be obtained from a comparison of pulsar data and 21-cm emission measurements. For high latitude pulsars this procedure is straight forward and reasonably free from assumptions. The resulting ionization ratios are high ($n_e/n_H = 0.39$). If this is compared with values as given by the theory of ionization and heating of interstellar gas by subcosmic rays, temperatures for the 'neutral' gas above 10^4 K are obtained. For low latitude pulsars this procedure depends to a much larger extend on the assumed distance of the objects and on the ionization theory. Here the values found are $n_e/n_H = 0.07$ and $T_e = 2000$ K.

Through the discovery of pulsating radio sources (Hewish *et al.*, 1968) a new parameter of the interstellar medium has become available to observation. From pulse delay measurements at different frequencies we immediately obtain

$$\mathrm{DM} = \int_0^d n_e \, \mathrm{d}s \quad [\mathrm{cm}^{-3}\,\mathrm{pc}]. \tag{1}$$

Due to the relative cosmic abundance of the chemical elements in interstellar space the source for the electrons in (1) must mainly be the hydrogen gas. Therefore it is reasonable to compare (1) with an expression that is formed similar, but with the electron density replaced by the density of neutral hydrogen

$$\mathrm{HM} = \int_0^d n_H \, \mathrm{d}s \quad [\mathrm{cm}^{-3}\,\mathrm{pc}], \tag{2}$$

the integral in (2) also extends from the observer up to the pulsar. Dividing (1) and (2) we have for an arbitrary distribution of n_e and n_H

$$\frac{\mathrm{DM}}{\mathrm{HM}} = \frac{\int_0^d n_e \, \mathrm{d}s}{\int_0^d n_H \, \mathrm{d}s} = \frac{\int_0^d \left(\frac{n_e}{n_H}\right) \cdot n_H \, \mathrm{d}s}{\int_0^d n_H \, \mathrm{d}s} = \overline{\left(\frac{n_e}{n_H}\right)}. \tag{3}$$

DM/HM is a weighted average of the ionization ratio n_e/n_H, the weighting factor being n_H, i.e. the volume density of *neutral hydrogen*. Assuming approximate pressure equilibrium in interstellar space, we have

$$n_H T_k \approx \mathrm{const} \tag{4}$$

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so that

$$\frac{\text{DM}}{\text{HM}} = \frac{\int_0^d \frac{n_e}{n_H} \cdot \frac{\mathrm{d}s}{T_k}}{\int_0^d \frac{\mathrm{d}s}{T_k}} = \overline{\left(\frac{n_e}{n_H}\right)}. \tag{5}$$

Hence DM/HM is the 'harmonic mean value' of the ionization ratio n_e/n_H.

Unfortunately HM as given in Equation (2) cannot be observed directly. While 21-cm absorption measurements do extend up to the unknown distance, *d*, of the pulsar, they do not give $\int n_H \, \mathrm{d}s$ but $\int (n_H/T_s) \, \mathrm{d}s$. T_s however, can be determined unambiguously only in exceptional cases.

If the radiation can be assumed optically thin the emission spectrum of the 21-cm line emission does give $\int_0^\infty n_H \, \mathrm{d}s$. Since the evidence available today points towards the pulsars as members of the disk population of our galaxy, we obviously must have

$$\text{HM} \leqslant \int_0^\infty n_H \, \mathrm{d}s = c \cdot \int_{-\infty}^{\infty} T_b(v) \, \mathrm{d}v = \text{HM}_{\text{obs}} \tag{6}$$

and thus

$$\text{DM}/\text{HM}_{\text{obs}} \leqslant \text{DM}/\text{HM} = \overline{(n_e/n_H)}. \tag{7}$$

Therefore the observed DM/HM is a *lower* limit to the harmonic mean ionization ratio.

Gordon *et al.* (1969) showed that the maximum optical depth of the 21-cm line emission for the direction of the three pulsars AP 0823, CP 0950 and CP 1133 is $\tau \ll 1$, so that (6) can be applied. For the other high latitude pulsars of Table I this cannot be proved, but as stated by Clark (1965), strong absorption is extremely unlikely to occur at high galactic latitude. Column 6 of this Table, therefore gives lower limits to the harmonic mean ionization ratio of the interstellar gas between pulsar and observer.

One possible explanation for the high ionization ratio might be given by the hypothesis, that the path intersects an HII region. An inspection of the distribution of O and B stars yielded however only very few objects, where this could be accepted (see Column 8).

The only other possibility is a high intrinsic ionization ratio of the interstellar medium. This is provided by the ionization theory of interstellar gas by subcosmic ray particles (Pikel'ner, 1968; Hjellming *et al.*, 1969; Field *et al.*, 1969; Spitzer and Tomasko, 1968) possibly supplemented by ionization by soft, diffuse X-rays (Silk and Werner, 1969). In this theory a unique relation exists between the ionization ratio and the electron temperature. If the theory of Hjellming *et al.* (1969) is used, the mean temperatures given in Column 7 of Table I are obtained.

These temperatures are considerably higher than those obtained by other means for the HI medium. They depend, however, only on the observed ratio DM/HM and

TABLE I

Observational data and electron temperatures for the gas in front of high latitude pulsars

(1) Object	(2) l^{II}	b^{II}	(3) DM	(4) HM	(5) τ_{max}	(6) DM/HM	(7) T_{min}	(8) H II reg
AP 0823	197	+32	19.2	92	<0.2	0.21	>10000	–
CP 0950	230	+44	3.0	86	<0.1	0.035	450	–
CP 1133	240	+70	5.0	97	<0.1	0.052	1000	–
MP 0450	217	−34	25	100	–	0.25	>10000	–
MP 0736	254	− 9	100	950	–	0.11	6500:	ζ Pup, γ^2 Vel
CP 0808	140	+34	5.8	80	–	0.07	2500	–
CP 0834	220	+26	12.8	130	–	0.10	5400	–
JP 0943	228	+42	20	98	–	0.20	>10000	–
AP 1237	254	+86	8.6	25	–	0.34	>10000	–
HP 1506	90	+53	19.6	50	–	0.39	>10000	–
AP 1541	18	+46	35	135	–	0.26	>10000	–
PSR 1642	14	+26	33	350	–	0.095	5000:	ζ Oph
MP 1727	341	− 9	140	600	–	0.23	>10000	I Sco
MP 1747	344	−11	40	540	–	0.074	2600	I Sco
PSR 2045	30	−33	11.4	250	–	0.046	720	–
PSR 2218	98	− 8	43.8	690	–	0.063	1600	–

on the ionization theory. It is quite well conceivable, that this theory still needs improvement, but it is difficult to imagine a theory, that gives ionization ratios of the interstellar gas as high as 0.4 together with temperatures much below a few 10^3 K.

If this interpretation is right, a considerable part of the observed line width of the 21-cm emission would be purely thermal in origin, so that the importance of internal turbulence in cosmic clouds could be smaller, than hitherto assumed. The general gas pressure of an intercloud medium with a temperature of several 10^3 K could be a great help to assist the stability of an average interstellar cloud.

The neutral hydrogen near the galactic plane cannot be considered to be optically thin, and therefore absorption effects in the H I gas must be taken into account when estimating eq. (2) for low latitude pulsars. It has been possible to measure the 21-cm absorption for 3 pulsars. Since the distance, d, to PSR 1749 probably is much smaller than the extend of the galactic disk in the same direction, the estimate for HM obtained from the 21-cm profiles is so much larger than the relevant value, that the resulting inequality is of little significance. There thus remain two objects with known absorption and spectra (CP 0328 and NP 0532). As shown by Mebold (1969) the absorption is mainly produced by a cold gas component. We therefore considered a two-component model where the cold gas produces the absorption, while the hot gas is responsible for most of the emission. For the cold gas an electron temperature of $T_e = 55$–60 K was inferred from the spectra. The amount of hot gas necessary to produce the remainder of the observed emission profile could then be determined for two model gas distributions, viz. model I, where the cold clouds lie in front of all the hot gas, and model II, where half of the hot gas is in front and half of it behind the cold clouds. The latter model is probably closer to reality.

Due to the uncertain value of the distance, *d*, of the two pulsars it is doubtful how much of the hot gas visible in the 21-cm emission spectrum is situated in front of the pulsar and thus has to be included in (7). That part of the observed DM which is produced by the cold gas can be determined from the measured amount of cold hydrogen and any one of the ionization theories. It is for both pulsars very small and all uncertainties in both the temperature and the ionization theory are of no consequence. The remaining part of the DM then must be caused by the 'hot gas component'. Depending on the distance assumed and which model distribution for the hot gas is acccpted values of $0.04 < DM/HM < 0.14$ are found, the most probable value being 0.07, corresponding to a $T_e = 2000$ K according to the theory of Hjellming *et al.* (1969). For a more extensive discussion of these low latitude pulsars, see Rohlfs *et al.* (1969).

There thus seems to be a marked difference between the mean n_e/n_H values obtained for high and low latitude objects indicating a temperature gradient within the hot HI gas component in the sense, that the temperature increases with increasing distance from the galactic plane.

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