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LOW-DENSITY IONIZED INTERSTELLAR GAS AS REVEALED BY INTERSTELLAR OPTICAL AND H I RADIO LINES

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ABSTRACT

Stars showing nonzero velocity optical interstellar lines usually have no corresponding H I radio line, but there often exists an H I cloud at the same velocity 5°–10° away in the sky. We suggest that in many cases the radio line is unobservable at the position of the star because the gas is ionized. This ionization might be caused by a global source of ionization rather than a more localized one such as the star itself because there may be a tendency for such stars to exist almost exclusively at negative Galactic latitudes. Existing spectra of extragalactic objects should, in some cases, have sufficient velocity resolution to apply to these problems.

Subject headings: interstellar matter — 21-centimeter radiation

I. INTRODUCTION

A number of authors have compared Na I and Ca II optical absorption lines with H I 21-cm emission lines. It is now well established that lines with $|v_{\rm LSR}| < 10$–20 km s^{-1} correlate well (Howard, Wentzel, and McGee 1963) and that other lines at "nonzero" velocities correlate poorly (Takakubo 1967; van Woerden 1967; Goldstein and MacDonald 1969; Habing, 1969; Gonaidzki 1972). Cases in which a radio line exists without an optical line can be rationalized by distance effects, with the star being in front of the gas.

However, when an optical line is seen without a radio line (in the terminology of Habing 1969, a "noncoincident" optical line), one must invoke a more sophisticated explanation. Habing has considered a number of possible physical explanations of such and narrowed the field to three: (1) the components originate in H II regions; (2) they originate in cold, dense regions in front of the star that are small compared with typical radio telescope beamwidths (10′–30′), conditions which will raise the ratio $N_{\rm (Ca\ II)}/N_{\rm (H\ I)}$ due to the high recombination rate; or (3) they originate in circumstellar clouds. He outlined two ways to rule out the second possibility, by using a radio telescope of much higher angular resolution and by taking optical spectra in the directions of strong radio sources to compare with H I absorption spectra. We have reobserved Habing's (1969) stars in the 21-cm line at Hat Creek, obtaining limits lower by a factor of about 20; unfortunately, however, it is impossible to definitively exclude the presence of a small, dense interstellar region occupying the tiny solid angle of the star no matter how sensitive the 21-cm observations. A new approach is required to decide among the alternatives.

II. NEW DATA

We have examined the H I distribution near some stars having noncoincident optical lines and believe there is evidence that these lines occur in ionized gas. Habing (1969) lists 17 stars of which 14 have $|b| > 10°$ and are thus covered by the Hat Creek survey of Heiles and Habing (1974). Many of these stars have weak, broad H I features, at or close to the same velocity as the optical lines, which appear *nearby* in the sky but *not* necessarily *at* the position of the star. Typical angles between the H I features and stars are 5°. The H I clouds show diameters of up to 10°, of course not centered near the star; they have total velocity widths of 5–10 km s^{-1} and brightness temperatures of 1°–2° K. This kind of association occurs definitely for six stars, probably for four, and does not occur for three; the optical line for one star lies outside the velocity range of the H I survey. Further definite associations might be revealed with higher sensitivity in the H I line, since the usual brightness temperatures seen in these associations are close to the sensitivity limit. On the other hand, the lack of an association is not inconsistent with the interpretation made below that noncoincident optical lines arise from ionized regions; if the whole cloud is ionized, it will appear nowhere in the 21-cm line.

Two definite associations are shown in figure 1. HD 25558 has a relatively narrow (4 km s^{-1}) and intense (3° K) feature nearby in angle ($l = 170°$–$180°$) which weakens somewhat at the position of the star ($l = 185°$). For a single 21-cm line profile taken at the position of the star, this feature would not be distinguishable as a distinct peak, but would instead appear only as a weak, extended line wing. Near HD 34816 ($l = 215°$) there is a weak, large-diameter feature ($l = 206°$–$214°$); on figure 1 the star seems to be located in the boundary region of this feature. Again, for a single 21-cm line profile this feature would appear only as an extended line wing, even at the most intense position near $l = 210°$.

III. INTERPRETATION

The circumstances shown in figure 1 seem to imply that these 21-cm features disappear at the position of the star because of ionization, caused either by random

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chance or perhaps even by the star itself. Values for the physical parameters of these clouds can be estimated. Typical equivalent widths for the Ca II components are only a few hundredths of an angstrom. Using the ionization equilibria and Ca/H abundance ratio given by Habing (1969) and a temperature of 3000° K, one can derive the emission measure, about 0.2 cm^{-6} pc, by assuming that the gas is fully ionized. The distance can be no more than that of the star, typically 300 pc; if the distance is 100 pc, the angular size of about 10° implies a diameter of 10 pc and a density of about 0.1 cm^{-3}. This density reminds us of the intercloud medium. However, the intercloud medium is supposed to be distributed smoothly in space instead of in clouds moving at specific velocities.

A curious feature of Habing's list is that of the 14 stars with noncoincident optical lines, all but one are at negative galactic latitudes. This is probably not a selection effect, because 69 percent of all stars he considered were at negative galactic latitudes. In his discussion of the physical conditions for these cases Habing could not understand the source of ionization

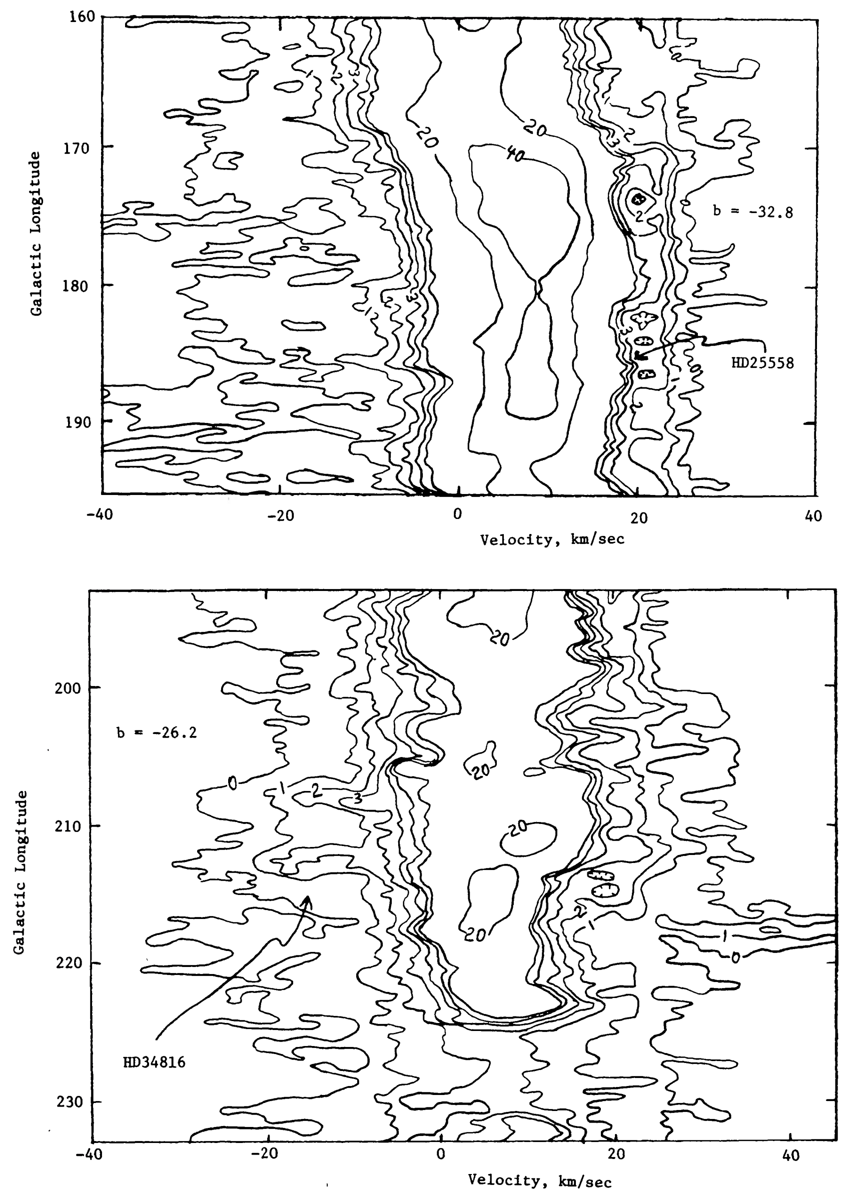

FIG. 1.—Contour maps of antenna temperature versus Galactic longitude and velocity, for fixed Galactic latitude. Each covers a star showing an interstellar Ca II line with no corresponding H I line. The position of the star and the velocity of the line are located at the tip of the arrow. Note that H I emission occurs nearby in angle. From Heiles and Habing (1974).

if the clouds were indeed ionized. Because of their apparent preponderance toward negative latitudes it is tempting to speculate that the source of ionization affects large volumes. The ionization could well result from a strong source of either cosmic rays, X-rays, or far-ultraviolet located in the negative galactic hemisphere; none of these components could easily traverse the amount of gas necessary to cross the galactic plane. It is interesting that most of the bright nebulae in Lynds's (1965) catalog not associated with a dust cloud (Lynds 1962) or an apparent exciting star are also located at negative galactic latitudes (Heiles and Jenkins 1974); these bright nebulae must have some agency responsible for their ionization, and it may be the same as that responsible for noncoincident optical lines.

On the other hand, the 21-cm line strengths associated with coincident optical lines at nonzero velocities are systematically much weaker than their counterparts at low velocities, which may imply that the gas is mostly, but not completely, ionized. Such lines occur in stars at both positive and negative galactic latitudes. In addition, Greenstein's (1968) list of interstellar lines seen in the spectra of hot stars at high positive galactic latitudes contains two noncoincident lines with velocities bordering on being nonzero (for Barnard 29, located in M13; and HD 137569) and two coincident optical lines with extremely weak associated H I lines (for HZ 22 and Feige 86). The accuracy of Greenstein's, velocities suffers from an inadequate number of plates, low spectral resolution, and blending; if his velocities are accurate, then their location at positive latitudes, as well as the systematically weaker H I lines associated with nonzero velocity coincident optical lines, implies that the preponderance toward negative latitudes seen in Habing's list is simply a statistical accident.

IV. NECESSITY FOR OPTICAL SPECTRA

The kind of nebulous association described above can be criticized as being due to chance. The whole northern sky has now been surveyed in the H I line (Weaver and Williams 1973; Heiles and Habing 1974), and only other types of data can increase the statistical body of information. Optical Hα data may help but probably lack the sensitivity required to map structures with emission measures of 0.2 cm^{-6} pc. Optical interstellar Ca II absorption lines offer an easy way to detect such low emission measures. Since this gas is ionized, it is unlikely to be observable in Na I lines (cf. Routly and Spitzer 1952; Siluk and Silk 1974).

Typical equivalent line widths range from 10 to 100 mÅ, and velocities need be measured only to within 10 km s^{-1} or so. The nonzero velocity components are usually separated by at least 20 km s^{-1} from the zero velocity peak. Some suitable observational material may already exist in the form of medium dispersion spectra of globular clusters, distant stars, and extragalactic objects having $|b| > 10°$ or so.

Some of the noncoincident interstellar lines are produced not in interstellar gas, but in circumstellar gas. As pointed out by a referee, the two components for HD 219188 listed by Habing (1969) do not appear in the list of Adams (1949); if their appearance in the spectrum taken by Münch and Zirin (1961) implies time variability, the lines are almost certainly circumstellar. However, if the picture presented in the present contribution is correct, optical interstellar lines with little or no corresponding H I lines should be correlated over angular distances of degrees in the sky. Observing distant stars with angular separations of up to several degrees should tell what fraction of the noncoincident components result from ionized gas, and the study of the distribution of the ionized components should enable us to discover the source(s) of ionization.

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