OPTICAL EMISSION LINES FROM WARM INTERSTELLAR CLOUDS: A DECISIVE TEST OF THE DECAYING NEUTRINO THEORY

D. W. SCIAMA

SISSA and ICTP; Trieste, via Beirut 2-4, 34013 Trieste, Italy; Nuclear and Astrophysics Laboratory, University of Oxford, Keble Road, Oxford OX1 3RH, England; sciama@sissa.it

Received 1998 June 11; accepted 1998 July 21; published 1998 August 24

ABSTRACT

Recently developed instruments such as the Taurus Tunable Filter and the Wisconsin Hα Mapper should be able to detect some or all of the optical emission lines Hα, [O i] λ6300, [S ii] λ6717, [N i] λ5200, and [N ii] λ6584 from warm interstellar clouds, such as those observed by Spitzer & Fitzpatrick along the line of sight to the halo star HD 93521. The strengths of these lines should resolve the debate as to whether the free electrons, which Spitzer & Fitzpatrick held responsible for the observed excitation of C ii in the clouds, are located mainly in the skins of the clouds or in their interiors. If the free electrons are indeed mainly located in the cloud interiors, then the substantial electron density derived by Spitzer & Fitzpatrick from cloud to cloud for the slow-moving clouds, when combined with their opacity to Lyman continuum radiation, lend strong support to the decaying neutrino theory for the ionization of the interstellar medium (Sciama). If the [O i] and [N i] lines are relatively strong but the [N ii] line is weak, then this would lend further, decisive, support to this theory, since decay photons are unable to ionize N, although its ionization potential is only 0.9 eV greater than that of H.

Subject headings: elementary particles — ISM: clouds

1. INTRODUCTION

The recent development of sensitive instruments, such as the Taurus Tunable Filter (Bland-Hawthorn & Heath Jones 1998) and the Wisconsin Hα Mapper (WHAM) (Reynolds et al. 1998b), for observing faint optical emission lines may make possible the detection of such lines from individual warm interstellar clouds. It would be of particular interest to study in this way the clouds observed by Spitzer & Fitzpatrick (1993, hereafter SF) along the line of sight to the halo star HD 93521. Their Hubble Space Telescope observations of the spectrum of this star revealed the presence of nine separate, warm (T ∼ 6000 K) absorbing clouds. Four of these clouds were slowly moving relative to the Sun, with the modulus of their heliocentric velocities being less than 19 km s⁻¹. The remaining five clouds had higher relative velocities, up to ~66.3 km s⁻¹. One of the absorbing ions that SF observed in each cloud was C ii* (J = 3/2), whose excitation they attributed to collisions between C ii ions and free electrons. From their data on the column density N(C ii*), they were able to derive the mean electron density n_e in each cloud and found that n_e is (i) substantial (~0.05–0.1 cm⁻³ in the slow clouds, depending on the assumed abundance of C) and (ii) the same in each of the slow clouds to a precision of ~10%. They argued that these free electrons are mainly located in the interiors of the clouds rather than in their skins (as later proposed by Domgørgen & Mathis 1994).

Further arguments in favor of the interior location of the free electrons were given by Sciama (1993b, 1997), who also claimed that, because each of the clouds has a column density of H i exceeding 5.6 × 10¹⁸ cm⁻² and therefore is opaque to hydrogen-ionizing photons near the Lyman edge, properties (i) and (ii) strongly suggest that the free electrons in the clouds are mainly produced by ionizing photons emitted by “dark” matter neutrinos in the clouds (Sciama 1990, 1993a). The decaying neutrino hypothesis, and the observational constraints on it, have been discussed in a number of papers (see, e.g., Overduin, Wesson, & Bowyer 1993; Dodelson & Jubas 1994; Overduin & Wesson 1997). A recent updating, prepared in anticipation of results that are soon expected from a satellite designed to search for the decay line due to neutrinos near the Earth (Bowyer, Edelstein, & Lampton 1997), can be found in Sciama (1998). Another possible ionizing source is cosmic rays, but this source would not be expected to produce the same electron density in each of the slow clouds (Sciama 1993b, 1997). The aim of this Letter is to point out that, if the strengths of the emission lines Hα, [O i] λ6300, [S ii] λ6717, [N i] λ5200, and [N ii] λ6584 could be measured in each of the clouds, it should be possible to settle these questions conclusively.

After this Letter was first submitted, I had the opportunity to see a conference report by McKee & Slavin (1998); they have made detailed calculations for photoionized gas along the line of sight toward HD 93521. They also mention an alternative explanation for the presence of a substantial abundance of free electrons inside the opaque clouds along this line of sight, namely, that each cloud is in fact comprised of many cloudlets, with enough space between the cloudlets that ionizing photons can penetrate in and provide the observed ionization (Slavin et al. 1998). This suggestion is ingenious, but it could not explain the rather precise proportionality between N(S ii), N(C ii*), and (N(H i) observed by SF in the slow (and presumably shock-free) clouds, which is predicted by the decaying neutrino theory for truly opaque clouds (Sciama 1993b, 1997).

2. OPTICAL EMISSION LINES FROM WARM INTERSTELLAR CLOUDS

With the exception of Hα, all the emission lines listed above require the emitting atoms or ions to be excited by electron collisions. Accordingly, for the lines to be observable, the clouds concerned would have to be warm (T > 3000 K). In fact, the SF clouds have T ∼ 6000 K, as judged by the widths of their 21 cm emission lines and their various absorption lines. The strengths of the optical emission lines, and also of the
absorption line of C II*, are each determined (except for Hα) by the product of the column density of the emitting atom or ion, the mean electron density, a function of the temperature through each cloud, and the collision cross section. As is well known from many observational and theoretical studies, it so happens that, for the elements O, S, and N, their interstellar abundances relative to H, when combined with a temperature \( \sim 10^4 \) K and their excitation cross section \( \sim 10^{-15} \) cm\(^2\) (Osterbrock 1989), lead to emission fluxes in the lines comparable to, but somewhat less than, the flux of Hα from the same diffuse region of the interstellar medium (ISM), if the dominant ionization state of the emitting atom or ion is the one that produces the lines concerned. This simple coincidence underlies our proposed use of these emission lines to test the decaying neutrino theory. We now consider each of these emission lines, and the absorption line of C II*, in turn.

2.1. C II*

We assume for simplicity that each cloud has a uniform total hydrogen density \( n_H \) and temperature \( T \) and that the hydrogen in the skin of each cloud is completely ionized. Then, from SF, we have

\[
N(C \, \text{II}*) = \frac{\xi_c n_{H} \chi_c}{T^{1/2}}(n_{n_{\text{H}}} l_n + n_{e} l_e),
\]

(1)

where \( \xi_c \) is the abundance of C relative to H, \( \chi_c \) is the collision strength, \( l_n \) and \( l_e \) are the total thicknesses of the skins and the interior of a cloud, respectively, and \( n_e \) is the electron density in the interior of a cloud. We have assumed that C II is the dominant ionization stage of C throughout each cloud. SF observed that, for the four slowly moving and presumably shock-free clouds, \( N(C \, \text{II}*) \ll N(H \, \text{I}) \). The natural conclusions from this observed proportionality are that (a) \( n_{n_{\text{H}}} l_n \ll n_{e} l_e \), (b) inside each of these clouds, \( n_{n_{\text{H}}} \gg n_{e} \), and (c) \( n_{e} \) is the same in each of these clouds. In that case,

\[
N(C \, \text{II}*) = \frac{\xi_c \chi_c}{T^{1/2}} n_e N(H \, \text{I}).
\]

(2)

Since \( \chi_c \) and \( T \) are known, one can derive \( n_{e} \) from this relation if \( \xi_c \) can be determined. Unfortunately, the C II absorption line is saturated in each cloud, and SF had to make an assumption about the value of \( \xi_c \). As we shall see below, this uncertainty can be avoided if the strength of the [S II] emission line can be measured, since \( N(S \, \text{II}) \) was directly observed in each cloud.

2.2. Hα

We have, for case B,

\[
H\alpha = \frac{1}{2} \alpha (n_{n_{\text{H}}}^2 l_n + n_{e}^2 l_e),
\]

(3)

where \( \alpha \) is the appropriate recombination coefficient. If the free electrons were mainly in the skin of each cloud, we would then have

\[
H\alpha = \frac{1}{2} \alpha n_{e}^2 l_e,
\]

\[
= \frac{1}{2} \alpha T^{1/2} \xi_c \chi_c N(C \, \text{II}^*). \tag{4}
\]

If \( \xi_c \) is solar, \( T = 6000 \) K, and \( N(C \, \text{II}^*) = 2.3 \times 10^{13} \) cm\(^{-2}\) (as it is in cloud 6), we would obtain \( H\alpha = 2 \times 10^5 \) photons cm\(^{-2}\) s\(^{-1}\) for this cloud alone.

On the other hand, if the free electrons were mainly in the interior of each cloud, we would have

\[
H\alpha = \frac{1}{2} \alpha T^{1/2} \frac{n_e}{\xi_c \chi_c} N(C \, \text{II}^*), \tag{5}
\]

which is less than the previous value by the (small) factor \( n_{n_{\text{H}}} / n_e \). It follows that a measurement of Hα from the clouds would determine the location of the free electrons and would constrain \( n_{n_{\text{H}}} / n_e \) if the electrons are found to be mainly in the interior. There exist unpublished measurements and upper limits on Hα in this direction obtained by R. J. Reynolds (1997, private communication), and these observations were used by Sciamma (1997) to deduce that the free electrons are indeed mainly in the interiors of the clouds and that \( n_{n_{\text{H}}} / n_e \sim \frac{1}{2} \) or \( \frac{1}{4} \), depending on whether the abundance of C is assumed to be solar or half-solar. It would be desirable to confirm this argument by obtaining definite values of Hα in each cloud from the new instruments. It might also be possible to observe limb brightening, if the angular resolution permits (J. Bland-Hawthorn 1998, private communication).

2.3. [O I] \( \lambda 6300 \)

This line has recently been detected in the diffuse ISM by WHAM (Reynolds et al. 1998a). Its ratio to Hα is so low (\( \sim 0.01 \)) that Reynolds et al. concluded that in the regions concerned, H must be highly ionized, since the ionization level of O is tied to that of H by charge exchange (Field & Steigman 1971). Since the line is only detectable from regions that contain appreciable densities of both neutral O and free electrons, it is ideal for testing the claim that the SF clouds are mainly neutral in their interiors but also that they contain an appreciable density of free electrons. In that case, we would have (Reynolds 1989)

\[
[O \, \text{I}] = 2 \times 10^{-9} T_4^{-0.45} \exp \left( -2.28 / T_4 \right) \xi_o n_e N(H \, \text{I}). \tag{6}
\]

For \( T_4 = 0.6, \xi_o = 8.5 \times 10^{-4}, n_e = 0.05 \) cm\(^{-3}\), and \( N(H \, \text{I}) = 2 \times 10^{19} \) cm\(^{-2}\), as found for cloud 6, one would obtain

\[
[O \, \text{I}] = 2.8 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1} \tag{7}
\]

for this cloud alone. A flux of this order would be measurable by the new instruments if the geocoronal [O I] line can be avoided. This might require confining the observations to the fast clouds. If a flux of this order is found, it would show conclusively that \( n_e \) is substantial in the interiors of the clouds. The observed flux would also determine \( \xi_o / \xi_c \) for each cloud.
2.4. $[S\text{ II}] \lambda 6717$

Since $S$ is expected to be mainly in the form $S\text{ II}$ in both the skin and the interior of each cloud, one would have (Reynolds 1989)

$$[S\text{ II}] = 7.3 \times 10^{-8} T_0^{-0.5} \exp (-2.14/T_0) n_e N(S\text{ II}), \quad (8)$$

if one assumes that, because SF found that $N(S\text{ II}) \propto N(H\text{ I})$, most of the $S$ II is in the interior of each cloud. For $T_0 = 0.6$, $n_e = 0.05$ cm$^{-3}$, and $N(S\text{ II}) = 3.2 \times 10^{14}$ cm$^{-2}$ (as it is in cloud 6), one would have

$$[S\text{ II}] = 4.1 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1} \quad (9)$$

for this cloud alone. Again, this is a measurable flux with the new instruments. Since $N(S\text{ II})$ was measured by SF in each cloud, the flux of $[S\text{ II}]$ can be used to derive the value of $n_e$ in each cloud, without having to make an assumption about the abundance of $S$ II that, in fact, SF found to be solar from the observed ratio $N(S\text{ II})/N(H\text{ I})$. This value of $n_e$ could then be used to evaluate both the ionization rate of $H$ and the abundance of $C$ and $O$ in each cloud.

2.5. $[N\text{ I}] \lambda 5200$

Although the ionization level of $N$ is no longer thought to be tied to that of $H$ by charge exchange (Osterbrock 1989), one would still expect that in the interiors of the clouds, $N$ would be mainly in the form $N$ I. If both $N$ and $O$ have solar abundances in the clouds, one has (Silk 1970)

$$\log \left( \frac{[O\text{ I}]}{[N\text{ I}]} \right) = 0.29 + 0.16 \frac{T_0}{T_4}. \quad (10)$$

Hence, for cloud 6, one would have

$$[N\text{ I}] = 7.8 \times 10^3 \text{ cm}^{-2} \text{ s}^{-1}. \quad (11)$$

If this line could be detected, one would again be able to test, as with the $[O\text{ I}]$ line, whether or not the free electrons are mainly located in the interiors of the clouds. In addition, one would be able to determine the abundance of $N$ in the clouds.

2.6. $[N\text{ II}] \lambda 6548$

A key question for the decaying neutrino theory is whether or not the decay photons can ionize $N$ (ionization potential 14.5 eV) as well as $H$ (13.6 eV). As pointed out by Sciamma (1995), if the extragalactic hydrogen-ionizing flux at zero redshift is less than $10^5$ photons cm$^{-2}$ s$^{-1}$ (as claimed by Vogel et al. 1995 and by Donahue, Aldering, & Stocke 1995 from their Hx observations of intergalactic neutral H clouds), then the energy of a decay photon must be less than $\sim 13.7$ eV, so that $N$ would not be ionized by decay photons. If, however, $N$ is ionized in clouds by the same mechanism as is $H$, then a comparison of the photoionization and recombination rates of $N$ and $H$ suggests that $N$ will have the same order of magnitude as $H$ for $H$. By contrast, if the $H$ in the interiors of the clouds is mainly ionized by decay photons, then the ionization level of $N$ in the interiors of the clouds would be much less than that of $H$.

One could determine $N/N$ in the cloud interiors if one could measure both $[N\text{ II}] \lambda 6584$ and $[N\text{ I}] \lambda 5200$ in the clouds. This follows because one has (Reynolds, Roesler, & Scherb 1977)

$$[N\text{ II}] = \frac{\exp (0.57/T_4) N\text{ II}}{N\text{ I}} \quad (12)$$

$$[N\text{ I}] = \frac{N\text{ II}}{N\text{ I}} \quad (13)$$

If one finds that $N$ has the same order of magnitude as $N$, as determined by the Hx data, then a conventional mechanism for the ionization of $H$ would be indicated. However, if $N/N \ll n_e/n_e$, then the decaying neutrino theory would be confirmed.

3. CONCLUSIONS

We conclude that observations of optical emission lines from the warm interstellar clouds along the line of sight to the halo star HD 93521 could (a) decide whether their free electrons are mainly located in the skins or in the interiors of the clouds, (b) provide a measurement of the mean electron density in each cloud free of uncertain assumptions about element abundances, (c) determine the abundances of the elements concerned in the clouds, and (d) determine whether $N/N$ in the clouds is comparable to or much less than $H/N$. If it is found to be much less, this would provide decisive evidence in favor of the decaying neutrino theory, whose photons are unable to ionize $N$ although its ionization potential exceeds that of $H$ by only 0.9 eV.

I am grateful to Ron Reynolds for his crucial help, to him and Joss Bland-Hawthorn for their comments on the manuscript, and to Chris McKee for sending me a copy of McKee & Slavin (1998) and for a very helpful correspondence. I am also grateful to the MURST for their financial support of this work.

REFERENCES

Bland-Hawthorn, J., & Heath Jones, D. 1998, Publ. Astron. Soc. Australia, 15, 44

Bowler, S., Edelstein, J., & Lampot, M. 1997, ApJ, 485, 523

Dedelson, S., & Juba, J. M. 1994, MNRAS, 266, 886

Domgörgen, H., & Mathis, J. S. 1994, ApJ, 428, 647

Donahue, M., Aldering, G., & Stocke, J. T. 1995, ApJ, 450, L45

Field, G. B., & Steigman, G. 1971, ApJ, 166, 59

McKee, C. F., & Slavin, J. D. 1998, Interstellar Turbulence, ed. P Franco & A. Carraminana (Cambridge: Cambridge Univ. Press), in press

Osterbrock, D. E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley: University Science Books)

Overduin, J. M., & Wesson, P. S. 1997, ApJ, 483, 77

Overduin, J. M., Wesson, P. S., & Bowyer, S. 1993, ApJ, 404, 1

Reynolds, R. J. 1989, ApJ, 345, 811

Reynolds, R. J., Hausen, N. R., Tufte, S. L., & Haffner, L. M. 1998a, ApJ, 494, L99

Reynolds, R. J., Roesler, F. L., & Scherb, F. 1977, ApJ, 211, 115

Reynolds, R. J., Tufte, S. L., Haffner, L. M., Jaehnig, K., & Percival, J. W. 1998b, Publ. Astron. Soc. Australia, 15, 14

Scrim, D. W. 1990, ApJ, 364, 549

Scrim, D. W. 1993a, Modern Cosmology and the Dark Matter Problem (Cambridge: Cambridge Univ. Press)
Sciana, D. W. 1993b, ApJ, 409, L25
———. 1995, ApJ, 448, 667
———. 1997, ApJ, 488, 234
———. 1998, A&A, 335, 12
Silk, J. 1970, ApJ, 161, L37

Slavin, J. D., McKee, C. F., Hollenbach, D. J., & Tielens, A. G. G. M. 1998, in preparation
Spitzer, L., & Fitzpatrick, E. L. 1993, ApJ, 409, 299 (SF)
Vogel, S. M., Weymann, R., Rauch, M., & Hamilton, T. 1995, ApJ, 441, 162