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WHAT IONIZES THE INTERSTELLAR HYDROGEN TOWARD PSR 0950+08 AND PSR 0823+26?

R. J. REYNOLDS
Department of Physics, University of Wisconsin-Madison
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ABSTRACT

The column densities of free elections along the two well-defined line segments to the pulsars PSR 0950+08 ($l = 229°$, $b = +44°$; $d = 127 \pm 13$ pc; $N_{H^+} = 9.2 \times 10^{18}$ cm^{-2}) and PSR 0823+26 (197°, +32°; 357 ± 80 pc; 6.0×10^{19} cm^{-2}) cannot be accounted for by H II regions surrounding nearby B stars or known hot white dwarf stars. The nearest O stars with Lyman continuum luminosities capable of producing the ionization are approximately 300–400 pc from the line segments. The existence of the ionized gas seems to imply either (1) very long mean free path lengths for the absorption of Lyman continuum photons within the interstellar medium, and thus a morphology for the interstellar H I that is very different from that usually depicted, (2) Lyman continuum luminosities for early B or hot white dwarf stars that are more than an order of magnitude larger than the currently accepted values, or (3) an additional, as yet unrecognized source of ionization within the Galactic disk.

Subject headings: interstellar: matter — nebulae: H II regions — pulsars

I. INTRODUCTION

Pulsar dispersion measures and the faint interstellar Hα background indicate substantial ionization of interstellar hydrogen outside bright, localized H II regions (see reviews by Kulkarni and Heiles 1987, 1988; Reynolds 1989*b*). The origin of this ionized gas is not well understood. It has been suggested that this gas is associated with transition regions between cool H I clouds and a pervasive, hot, "coronal" gas and that it is ionized by ambient interstellar radiation (McKee and Ostriker 1977). On the other hand, if *warm* (10^4 K) atomic hydrogen occupies most of the interstellar volume (e.g., Kulkarni and Heiles 1987; Cox 1989), the ionized gas may be associated primarily with extended H II regions within a warm, low-density intercloud medium. Of the known sources of ionizing radiation in the Galactic disk only O stars appear to have a flux that is large enough to produce the ionization (Reynolds 1984). However, the scale height (~1.5 kpc; Reynolds 1989*a*; Manchester and Taylor 1977) of the ionized gas is much larger than that of both the H I clouds and the O stars, and the ionization is often found along lines of sight that are far from O stars (Reynolds 1989*a*, 1987, 1984). Moreover, the optical emission-line spectrum of the diffuse ionized gas is observed to be significantly different from that of faint, extended H II regions associated with O and early B stars (Reynolds 1985, 1988*a*).

Using VLBI techniques Gwinn *et al.* (1986) obtained parallax-determined distances of 127 ± 13 pc for the pulsar PSR 0950+08 and 357 ± 80 pc for the pulsar PSR 0823+26. The dispersion measures of these pulsars are 2.969 ± 0.001 cm^{-3} pc and 19.4634 ± 0.0007 cm^{-3} pc, respectively (Craft 1970; Manchester and Taylor 1981). Therefore, free electron column densities are now known along two well-defined line segments in the solar neighborhood. These line segments are separated by about 28° and have their far end points at distances $z \approx +90$ pc (PSR 0950+08) and +190 pc (PSR 0823+26) above the Galactic plane. They do not intersect any known H II regions. The lack of any departure of the pulse dispersions from the lowest order ν^{-2} frequency dependence (e.g., Goldstein and James 1969), the low values of 0.7 and 0.4 μG for the longitudinal component of the magnetic field along the line segments derived from the Faraday rotation measures and the dispersion measures (Manchester 1974), plus the general absence of Faraday rotation intrinsic to pulsars (Manchester 1972) indicate that the electron column densities are truly interstellar. The corresponding mean volume densities are 0.023 cm^{-3} and 0.054 cm^{-3}, respectively. This indicates extensive ionization in the solar neighborhood similar to the large-scale, diffuse ionization within the Galactic disk revealed by much more distant pulsars (e.g., Weisberg, Boriakoff, and Rankin 1979; Ables and Manchester 1976; Reynolds 1989*a*) and by the interstellar emission-line background. Therefore, an identification of the source(s) of this local ionization could provide valuable clues about the origin and nature of the diffuse interstellar ionization. An examination of the locations of all O and B stars and known hot white dwarf stars near these two line segments and the ability of each star to produce the observed pulsar dispersion measures has been carried out. The results are presented below.

II. H II REGIONS SURROUNDING LUMINOUS STARS

a) Maximum Distance of the Ionizing Star from the Line Segment

The column density N of electrons along a chord that intersects a spherical H II region, equal to $2fn_e R$ along the diameter, is given by

$$N = \left[\frac{3}{\pi\alpha}\frac{L}{R}f\left(1 - \frac{\Delta^2}{R^2}\right)\right]^{1/2}, \qquad (1)$$

where R is the radius of the region, Δ is the perpendicular distance between the ionizing star and the chord, L is the Lyman continuum photon luminosity of the star, f is the fraction of the spherical volume occupied by ionized gas with density n_e, and α is the effective hydrogen recombination coefficient. For a given star with luminosity L, a particular value of N can be obtained for a range of values of Δ; the values of Δ

will depend upon f and R according to equation (1). For a given f, the maximum value of Δ can be obtained in the usual way by differentiating Δ with respect to R and setting the result equal to zero. This gives

$$\Delta \leq \frac{2}{\pi\sqrt{3}} \frac{f}{\alpha} \frac{L}{N^2} . \quad (2)$$

This distance has a maximum value Δ_{max} for a uniformly filled (i.e., $f = 1$) H II region. If the gas is clumped into clouds, then the star must be closer to the line of sight than Δ_{max}, except for the very special case in which the H II region is a thin, hollow shell or a portion of a shell tangent to the line of sight. In that case the star can produce a column density N from a distance of $\sqrt{3}\,\Delta_{max}$. Even larger values of Δ for a given L are possible, if the line of sight coincided with the thin, ionized surface of a sufficiently extended flat sheet or straight cylinder of gas. However, such geometries are extremely contrived, particularly when the column densities in two separate directions must be explained, and, therefore, they will not be considered in this analysis. When the column density is associated with a line segment of finite length D, an additional constraint on Δ arises; namely, the density within the H II region cannot be lower than N/D. Therefore, a star with a large L, which can produce an H II region with a diameter much larger than D, cannot be farther from the line segment than the radius of an H II region of density N/D; thus

$$\Delta < \left(\frac{3}{4\pi\alpha} \frac{fLD^2}{N^2}\right)^{1/3} . \quad (3)$$

Plots of Δ_{max} versus L are shown in Figures 1*a* and 1*b* for the PSR 0950+08 and PSR 0823+26 line segments, respectively. The heavy solid line refers to a uniformly filled sphere, and the dashed line refers to a tangent shell. The adopted value for the effective hydrogen recombination coefficient α is 3.1×10^{-13} $cm^3\ s^{-1}$, which corresponds to an electron temperature T of 8000 K; near 10^4 K α is proportional to $T^{-0.806}$ (Martin 1988; case B). The electron temperature along these particular line segments has not been measured. However, observations of interstellar emission lines, which appear to originate from the same regions that produce the pulsar dispersion measures (see Kulkarni and Heiles 1987, 1988; Reynolds 1989*b*), indicate a temperature $\sim 10^4$ K with a best-fit value of 8000 K (Reynolds 1985).

The additional lines in Figures 1*a* and 1*b* refer to cases in which the column density N is produced by more than one ionizing star. For example, a cluster of n stars, each with a Lyman continuum photon luminosity L/n could produce an H II region equivalent to that surrounding a single star of

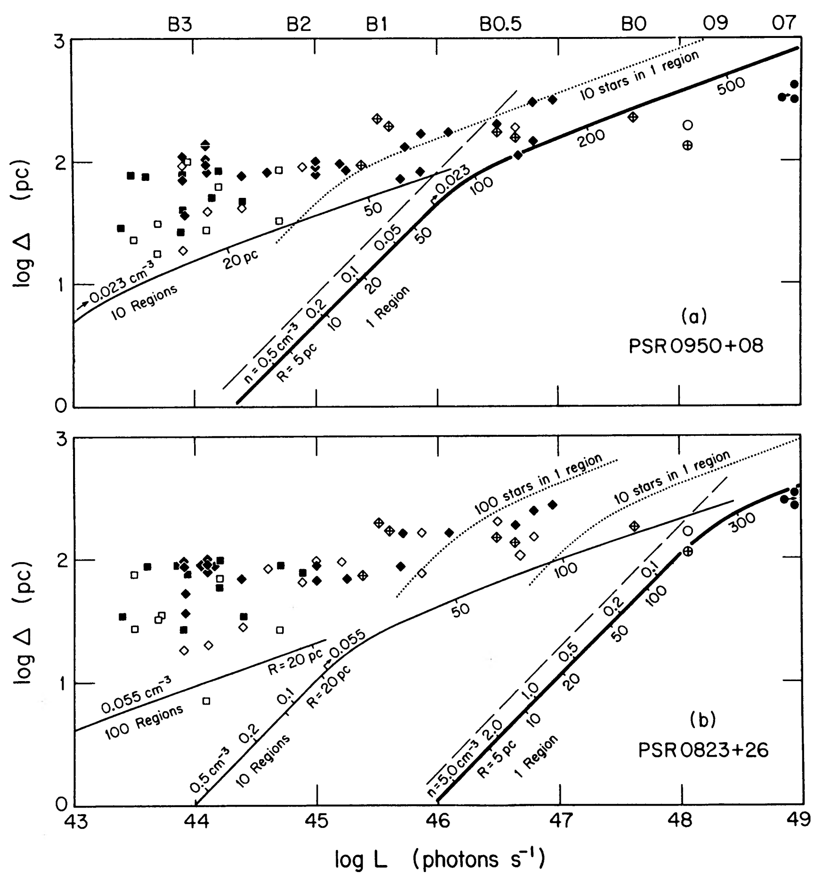

FIG. 1.—The maximum distance from the line of sight at which a star or group of stars can produce the observed electron column densities along the PSR 0950+08 (*a*) and PSR 0823+26 (*b*) line segments—*solid lines*: 1, 10, 100 H II regions intersected by the line segment; *dashed line*: a thin, H II shell tangent to the line segment; *dotted lines*: 10, 100 stars ionizing a single H II region. The radii R and electron densities n of the H II regions are indicated along Δ_{max} vs. L curves. Also plotted are the potential ionizing stars listed in Table 1—*circles*: O stars; *diamonds*: B stars; *squares*: hot white dwarf stars. The location of the star denotes its distance Δ from the line segment and its Lyman continuum photon luminosity L. Filled symbols denote stars with $0 < s < D$ (see text). Crosses within some of the open symbols denote stars in the Sco OB2 association.

luminosity L. The values of Δ_{max} for clusters of 10 and 100 stars are indicated by dotted lines. Alternatively, N could be produced by n separate H II regions along the line segment with each region contributing a column density of approximately N/n. If the regions are small so that the sum of their diameters is less than the length of the line segment, then Δ_{max} for the n stars would be n^2 larger at a given L than Δ_{max} for the case of a single star (eq. [2]). If the H II regions are large, then the value of Δ_{max} approaches the radius of an H II region of density N/D (eq. [3]) and is independent of the number of regions contributing to N. The values for Δ_{max} corresponding to 10 and 100 H II regions intersected by the line segment are denoted by the lighter solid lines.

These Δ_{max} versus L curves can be used to identify which stars or clusters of stars *may* be capable of producing the observed column densities and which are not (see § III below). For example, if the column density is produced by a single H II region, then there must be a star with a luminosity L and a distance Δ from the line segment that places it on or below the heavy "one-region" line; if the column density is produced by 10 (100) H II regions intersected by the line segment, then 10 (100) stars must lie below the 10-region (100-region) curve. It is very unlikely that there would be a large number of thin shells tangent to the line segment.

b) *Constraints Provided by the Intensity of the Interstellar Hα Line*

The gas densities and H II region radii that would be associated with stars located along the Δ_{max} versus L curves are also shown in Figures 1*a* and 1*b*. Note that at large radii R, where equation (3) applies, the entire line segment is within the H II region(s), $\Delta_{max} \approx R$, and the electron density is at the minimum value of N/D. Constraints on the density and the extent of the ionized gas along the line segments are provided by measurements of the interstellar Hα intensity toward the two pulsars. Scans of Hα obtained with the Wisconsin large-aperture Fabry-Perot spectrometer reveal interstellar Hα emission with an intensity of $1.3 \pm 0.2R$ and $2.7 \pm 0.4R$ toward PSR 0950+08 and PSR 08234+26, respectively (Reynolds 1984, supplemented by higher signal-to-noise observations toward PSR 0823+26). These intensities imply emission measures EM $\simeq 2.9$ cm^{-6} pc and 6.1 cm^{-6} pc, respectively. Therefore, along the line segments the ionized gas must have a local density $n_e \leq \mathrm{EM}/N$ and have an extent $l \geq N^2/\mathrm{EM}$, corresponding to $n_e \leq 1.0$ cm^{-3} and 0.31 cm^{-3} and $l \geq 3.0$ pc and 62 pc, respectively, for PSR 0950+08 and PSR 0823+26. Only limits can be derived because some (or most) of the emission measure may be due to ionized gas located beyond the pulsar, especially toward the very nearby PSR 0950+08. These upper limits on n_e imply that, if the column densities are produced by single H II regions along the PSR 0950+08 and PSR 0823+26 segments, the ionizing stars must have, respectively, $L > 10^{44}$ s^{-1}, corresponding to a star of type B3 or earlier, and $L > 10^{47}$ s^{-1}, corresponding to B0 or earlier.

III. IDENTIFYING CANDIDATE STARS

Stars that are potential sources of ionization for the line segments are listed in Table 1. Listed, in order of increasing distance from the Sun, are the name of the star, its spectral type, Lyman continuum luminosity L, distance d from the Sun, and two parameters Δ and s, which denote the position of the star relative to each of the line segments. The parameter Δ is the perpendicular distance between the star and the line of sight that includes the line segment, and s is the distance from the Sun along the line of sight at which the minimum distance occurs. Positive values of s are in the direction of the pulsar. Included in Table 1 are all the stars from the catalogs by Lesh (1968, 1972) that have spectral types B3 and earlier and are within about 100 pc of at least one of the line segments, as well as all stars B1 and earlier within about 200 pc and B0 stars within 300 pc of the line segments. The B3 V stars are complete out to about 350 pc from the Sun (for $E_{B-V} = 0$), approximately the entire length of the longer PSR 0823+26 segment, and the B1 and B0 stars are complete out to about 400 pc and 650 pc, respectively (for $E_{B-V} = 0.3$). Also included are known hot white dwarf stars within about 100 pc of the line segments, and the five nearest O stars. The spectral types and distances of the O and B stars are from Lesh (1968, 1972), and their Lyman continuum luminosities are from Panagia (1973). The spectral types are generally consistent with those adopted by Hoffleit (1982). A couple of potentially important discrepancies, θ Car and γ Cas, are discussed in § IV. Also, according to Hoffleit, σ Sco and β Mon have companions with spectral types that are the same or earlier than that of the primary. For these two stars the values of L and the spectral types listed in Table 1 have been appropriately adjusted. The hot evolved stars are those with published distances or absolute magnitudes and temperatures (Bruhweiler and Kondo 1982; Holberg 1984; Paresce 1984*b*; Schönberner and Drilling 1984; Wray, Parsons, and Henize 1979; Wesemael, Green, and Liebert 1985; McCook and Sion 1984). Lyman continuum luminosities were computed based on the assumption that for effective temperatures in the range 50,000 K–100,000 K, which correspond to the temperature index 1 to 0 in McCook and Sion (1984), the spectral distribution closely resembles that of a blackbody, and therefore, $L \approx 8 \times 10^{43} L_{\odot}$ photons s^{-1}, where $L_{\odot}$ is the bolometric luminosity in solar units (Hills 1972).

The values of Δ and L for each star listed in Table 1 are plotted in Figure 1. For the PSR 0950+08 line segment nine B stars (α, β Cru; β, δ, τ Sco; γ Cas; θ Car; ϵ, ζ Per) and the five O stars (σ Sco, ζ Oph, ξ Per, ζ Pup, δ Ori) are below the "tangent shell" line and thus are candidates for further consideration, while for the PSR 0823+26 line segment *only the O stars* are candidates. All the candidate stars are located more than 100 pc from the two line segments. Ionization by a large number of closer, less luminous stars is ruled out by the almost total absence of such stars below the multiple region curves.

IV. EXAMINING THE INDIVIDUAL CANDIDATES

A star's location on or below the Δ_{max} versus L curve does not guarantee that it is capable of producing the observed electron column density along the line segment. First, the curves in Figure 1 refer to ionizing stars that are optimally positioned with respect to the line segments; specifically, $0 < s < D$ for H II regions with radii $R \ll D$, and $s = D/2$ for $R \gtrsim D$. Figure 2 illustrates the position of each of the candidate stars relative to each line segment; it does not give the relative positions between the stars. This figure shows that most of the stars are not optimally positioned and, therefore, are not as capable of providing the required electron column density as their positions in Figure 1 would suggest. Second, the presence of an emission nebula in the immediate vicinity of a star or a significant column density of neutral hydrogen between a star and the line segment could prevent the ionizing radiation from reaching the line segment. Finally, all the candidate stars have values of Δ that require H II regions with diameters larger than

TABLE 1

Potential Sources of the Ionization

				PSR 0950+08		PSR 0823+26	
Star	Spectral Type	log L (photons s^{-1})	d (pc)	Δ (pc)	s (pc)	Δ (pc)	s (pc)
HD 10144 (α Eri)	B3 V	43.91	21	19	−9	18	−10
WD 0109−264	DA1	43.5	30	23	−19	27	−14
HD 149499B	DO1	44.7	34	33	−7	26	−22
WD 2309+105	DA1	43.7	39	18	−35	32	−22
GD 153	DA1	43.4	40	29	+28	35	+19
WD 0050−332	DA1	43.7	41	31	−27	35	−22
HD 120315 (η UMa)	B3 V	43.91	41	37	+18	37	+18
WD 0549+158	DA1	43.9	45	39	+23	27	+36
G191−B2B	DA0	44.4	48	46	+14	34	+34
LSE 21	SdO	44.1	50	28	−41	7	−50
HD 193924 (α Pav)	B2.5 V	44.40	56	44	−35	28	−48
HD 175191 (σ Sgr)	B3 IV	44.11	57	41	−40	20	−53
HZ 43	DA1	44.2	65	51	+40	58	+29
HD 32630 (η Aur)	B3 V	43.91	76	72	+25	52	+55
WD 1544+008	DA1	43.5	78	78	+2	74	−23
WD 0104−331	DA1	44.2	79	62	−50	68	−40
HD 122451 (β Cen)	B1 III	45.87	81	81	+9	76	−28
HD 121263 (ζ Cen)	B2.5 IV	45.59	85	83	+19	82	−21
HD 116658 (α Vir)	B1 IV	45.70	86	71	+48	85	+13
HD 81188 (κ Vel)	B2 IV–V	45.0	89	80	+40	88	+12
Feige 24	DA1	44.7	90	85	−29	90	+5
HD 74195 (o Vel)	B3 IV	44.11	93	83	+43	92	+17
HD 35468 (γ Ori)	B2 III	45.25	93	85	+37	69	+63
HD 11415 (ϵ Cas)	B3 V	43.91	93	93	−9	87	+32
HD 45725 (β Mon)	B3 V + B3 + B3	44.21	98	78	+59	68	+70
HD 158427 (α Ara)	B2 V	44.89	98	91	−36	64	−74
HD 127972 (η Cen)	B1.5 V	45.21	98	97	+15	95	−27
WD 1302+283	DA1	43.6	99	75	+64	86	+48
HD 109668 (α Mus)	B2 IV–V	45.0	99	98	+14	95	−27
LSS 1362	SdO	44.2	100	81	+58	97	+25
HD 158926 (λ Sco)	B1.5 IV	45.38	103	94	−43	63	−82
HD 25204 (λ Tau)	B3 IV	44.11	103	103	+6	92	+46
HD 38622	B2 IV–V	45.0	104	90	+51	66	+81
HD 108248 (α Cru)	B0.5 IV + B1 V	46.68	114	111	+26	109	−22
PG 1034+001	DO	44.9	115	27	+112	76	+87
HD 29763 (τ Tau)	B3 V	43.91	117	113	+29	91	+74
HZ 21	DO	43.9	118	78	+89	89	+77
HD 50820	B3 IV	44.11	134	96	+94	79	+108
HD 147165 (σ Sco)	B1 III + 0.95 V	48.08	138	136	−23	112	−80
HD 111123 (β Cru)	B0.5 III	46.80	154	149	+37	151	−30
HD 143275 (δ Sco)	B0.5 IV	46.65	154	153	−13	133	−77
HD 41753 (ν Ori)	B3 IV	44.11	163	134	+92	92	+134
HD 42560 (ξ Ori)	B3 IV	44.11	169	138	+98	94	+140
HD 118716 (ϵ Cen)	B1 III	45.87	174	170	+37	168	−44
HD 144217 (β Sco)	B0.5 V	46.50	174	173	−17	150	−87
HD 52089 (ϵ CMa)	B2 II	45.72	187	155	+104	161	+95
HD 5394 (γ Cas)	B0.5 IV	46.65	194	189	−42	189	+43
HD 149757 (ζ Oph)	O9.5 V	48.08	200	195	−42	166	−111
HD 143018 (π Sco)	B1 V + B2	45.61	200	199	−16	172	−102
HD 44743 (β CMa)	B1 II–III	46.10	203	172	+107	164	+120
HD 93030 (θ Car)	B0.5 V	46.50	205	196	+60	204	−17
HD 144470 (ω Sco)	B1 V	45.52	225	224	−23	193	−115
HD 149438 (τ Sco)	B0 V	47.63	236	229	−53	183	−150
PG 0929+270	DO	43.94	298	100	+281	75	+288
HD 24760 (ϵ Per)	B0.5 III	46.80	302	300	+31	252	+167
HD 24398 (ζ Per)	B1 Ib + B0.5 V	46.96	322	321	+25	275	+167
HD 24912 (ξ Per)	O7.5 III	48.98	322	320	+32	270	+176
HD 66811 (ζ Pup)	O5	49.71	405	328	+237	373	+159
HD 36486 (δ Ori)	O9.5 Ia	48.97	463	415	+205	350	+303

the length of the line segments. The values of Δ_{max} for such H II regions were calculated for the case in which the region has a uniform electron density of N/D and just envelops the line segment. If the ionized gas does not occupy the entire line segment, the gas is clumped into clouds, or, if the ionization extends beyond the end points of the line segment (a likely situation for the shorter PSR 0950+08 segment; see § V), then the required value of Δ will be smaller than the plotted Δ_{max} curve. For these reasons each candidate star must be examined individually, and the distribution of gas in the local interstellar medium taken into account in order to determine which stars (if any) are capable of producing the observed value of N.

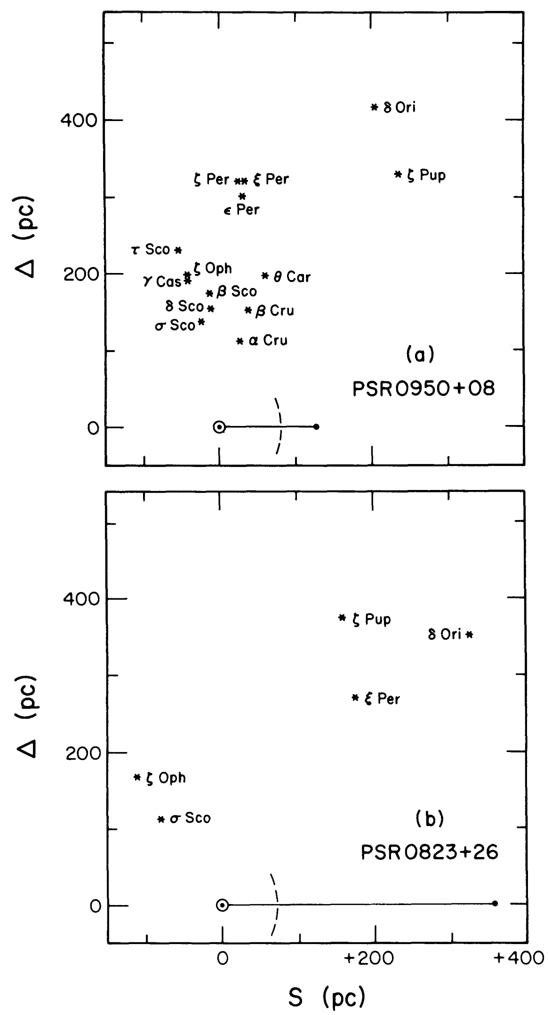

FIG. 2.—The location of each of the candidate stars relative to the Sun-pulsar line segments. The dashed arc indicates the estimated extent along the line segment of the X-ray emitting cavity that surrounds the Sun.

a) *Candidate Stars for the PSR 0950+08 Line Segment*

i) *α Cruxis*

The candidate star nearest to the PSR 0950+08 line segment is α^1 Cru, the most luminous member of a B0.5 IV + B1 V + B4 IV triple system. A uniformly filled ($n_e =$ 0.023 cm^{-3}) H II region that just envelops the line segment ($R = 150$ pc) would require that α Cru have a $L = 7 \times 10^{46}$ s^{-1}. Although this luminosity is higher than that listed for α Cru in Table 1, Lyman continuum fluxes for B stars are model-dependent (see Fig. 2 in Panagia 1973), and, therefore, such a high luminosity for α Cru probably cannot be ruled out. As Figure 1*a* indicates, a suitably contrived shell-like H II region would lower the required Lyman continuum luminosity from α Cru. For example, a thin, 111 pc radius shell tangent to the line segment at a distance of about 26 pc from the Sun would require a luminosity $L = 1.4 \times 10^{46}$ s^{-1}. Given the constraints on the local gas density along this line segment (i.e., $n < 1$ cm^{-3}; § II*b* above), such a shell must have a thickness ΔR and occupation pathlength l along the segment confined to the ranges $0.01 < \Delta R < 3$ pc and $3 < l < 52$ pc, respectively. An ionized shell occupying more than the first 52 pc of the line segment would require a larger L. For example, a shell or portion of a shell that just enveloped the entire line segment would require $L = 4.2 \times 10^{46}$ s^{-1}, approximately the luminosity listed for α Cru, and a shell that occupied only the far portion of the line segment would require a still larger L (see below).

Thus the Lyman continuum flux from α Cru could be just about enough to produce the electron column density toward PSR 0950+08, if the gas between the star and the line segment has a density $n \leq 0.023$ cm^{-3} *and* the ionized gas either occupies almost the entire line segment at a density of 0.023 cm^{-3} or is confined to a higher density region within about 50 pc of the Sun. It appears unlikely that any of these conditions are satisfied. First, deep, narrow-band Hα photographs by Sivan (1974) of the region of the sky containing α Cru show Hα nebulosity over the region with an apparent enhancement near the star. If this nebulosity is produced in part by α Cru, its emission measure of ~50 cm^{-6} pc and extent of a few parsecs imply gas densities $n \geq 1$ cm^{-3} near the star. Also, Lyα measurements of the H II column density to α Cru indicate a mean *neutral* hydrogen density of about 0.2 cm^{-3} between the Sun and the star (Bohlin *et al.* 1983), nearly a factor of 10 larger than the maximum *ionized* hydrogen density that would allow α Cru's H II region to reach the required 111–150 pc radius in the direction of the Sun-PSR 0950+08 line segment. Note that unit optical depth to Lyman continuum photons corresponds to a mean H I density $n \sim 10^{-3}$ cm^{-3}. Of course, it is possible that the Hα nebulosity is not associated with α Cru and the H I column density is high along the line to the Sun but not toward the remainder of the line segment (see Fig. 2*a*). Second, the ionized gas is almost certainly not uniformly distributed along the PSR 0950+08 line segment. Within about 100 pc of the Sun there appears to exist a region of X-ray emitting gas, within which the most prevalent conditions are a temperature near 10^6 K and a density of about 4×10^{-3} cm^{-3} (e.g., Sanders *et al.* 1977). Toward PSR 0950+08 this cavity appears to extend out to a distance of about 80 pc (Cox and Snowden 1986; Cox and Reynolds 1987). If this model for the local interstellar medium is correct, the ionized gas responsible for the pulsar dispersion measure must be confined primarily to the outer 47 pc of the PSR 0950+08 line segment and have an electron density $n \gtrsim 0.056$ cm^{-3}. The hot cavity then accounts for only about 10% of the total electron column density. The required flux in this case is $L \gtrsim (2–4) \times 10^{47}$ s^{-1}, where the range in values denotes an ionized shell, or portion of a shell, that just envelops the outer 47 pc of the line segment and a uniformly filled H II region between α Cru and the ionized portion of the line segment, respectively. Decreasing the distance to α Cru would change very little the required radius of the H II region (see Fig. 2*a*) and thus lower the limits on L. Bohlin *et al.* (1983), for example, list a distance of 99 pc rather than 114 pc, which would reduce the required L by only 15%.

Thus the α Cru system is a possible source of the ionization for the PSR 0950+08 line segment only if its Lyman continuum luminosity is at least 3–8 times larger than that listed by Panagia (1973) for its spectral type or the standard model for the local interstellar medium is incorrect. Even then its viability as the ionization source would depend upon the H I column density between the Sun and α Cru not being representative (by more than two orders of magnitude) of the H I column density between the star and the remainder of the line segment.

ii) *β Cruxis*

Many of the arguments made about α Cru also apply to the B0.5 giant β Cru, the candidate star next nearest the PSR

0950+08 line segment ($\Delta = 149$ pc). Beta Cru is located in a region of faint Hα nebulosity (Sivan 1974); however, the relationship between the star and the nebulosity is uncertain. There are no H II column density estimates available. If a uniformly filled H II region with a density of 0.023 cm^{-3} and a radius of 174 pc just enveloped the line segment, then the required L is 1.1×10^{47} s^{-1}, which is larger than the listed value of 6.3×10^{46} s^{-1}. The required L can be reduced to 1.9×10^{46} s^{-1} for a thin shell tangent to the line segment at $s = 37$ pc from the Sun. However, when the existence of the local X-ray cavity is taken into account, the required minimum Lyman continuum luminosity, $L \gtrsim (2\text{–}6) \times 10^{47}$ s^{-1}, is 3 to 10 times that listed for a star of β Cru's spectral type.

iii) *θ Carinae*

The B0.5 V star θ Car is 196 pc from the line segment. A uniformly filled H II region would require $L = 1.9 \times 10^{47}$ s^{-1} to account for the observed column density, a factor of 6 larger than the 3.2×10^{46} s^{-1} listed for θ Car. If the spectral type of θ Car is B0 V (Hoffleit 1982) rather than B0.5 V, then the star's ionizing flux would be sufficient. However, the presence of a faint arc of Hα nebulosity about 1° to the northwest of θ Car (Sivan 1974) and the large H I column density of 5×10^{20} cm^{-2}, which corresponds to $\langle n_{\rm H\,I} \rangle = 0.8$ cm^{-3}, cast doubt on the existence of such a large, low-density H II region around this star.

iv) *γ Cassiopeiae and ε and ζ Persei*

The ionizing luminosity listed for γ Cas is less than 10% that needed to produce the PSR 0950+08 electron column density. If its spectral type is B0 IV (Hoffleit 1982) rather than B0.5 IV, and if the distance is unchanged, then the ionizing flux would be at the minimum required value for a thin, ionized shell that just includes the outer 47 pc of the line segment. However, γ Cas is surrounded by an H II region (S185) and has an H I column density of 1.5×10^{20} cm^{-2} ($\langle n_{\rm H\,I} \rangle = 0.25$ cm^{-3}). Its position relative to the line segment ($s < 0$) suggests that this absorbing gas probably shields the remainder of the line segment from any Lyman continuum radiation that may escape the H II region.

The more distant B stars ϵ and ζ Per ($\Delta \approx 300$ pc) also have insufficient ionizing fluxes by factors of at least 5 to 6, respectively. These stars have high H I column densities and observable reddening. The possible effect of including the flux from the much more luminous O star, ξ Per, in the Per OB 1 association is discussed in subsection (vii) below.

v) *β, δ, σ, and τ Scorpii*

The luminous stars in the Sco OB2 association do not appear to be capable of producing the ionization, either individually or collectively. The minimum flux required from β and δ Sco, corresponding to a shell or a portion of a shell that just envelops the outer 47 pc of the line segment, is 8–14 times larger than the luminosities listed in Table 1. Tau Sco would need a luminosity about twice its listed value. On the other hand, approximately 70% of the Lyman continuum flux from the Sco OB2 association probably is produced by the O9.5 V member of the σ Sco system (Hoffleit 1982). This star's flux is 3 times larger than the minimum flux of 4×10^{47} s^{-1} required from a star at its location. However, the presence of clearly associated Hα nebulosity around each star (e.g., S9 around σ Sco) as well as the substantial H I column densities of 2.2×10^{21}, 3.1×10^{20}, 1.2×10^{21}, and 1.4×10^{21} cm^{-2} for σ, τ, β and δ Sco, respectively (Stokes 1978), suggest that most of the ionizing photons are absorbed in the immediate vicinity of the stars. Because of the locations of the stars relative to the segment (Fig. 2*a*), the absorbing gas observed in the vicinity of the stars probably also shields the remainder of the line segment from the stars' ionizing radiation.

vi) *ζ Ophiuchi*

Similarly, the Lyman continuum luminosity of the O9.5 V star ζ Oph would be sufficient to account for the ionization, if the stars' radiation were absorbed by a shell or a portion of a shell having an outer radius of 260 pc and an inner radius of 230 pc that just envelops the outer 47 pc of the line segment. However, ζ Oph is surrounded by an H II region (S27) that appears to be ionization-bounded (Celnik and Weiland 1988; Reynolds and Ogden 1982). Furthermore, there is a large column density of atomic and molecular gas toward ζ Oph, much of which appears to be immediately in front of the star (Black and Dalgarno 1973; Morton 1975), which would shield the PSR 0950+08 line segment from the ionizing radiation.

vii) *The Remaining O Stars*

Because of their higher Lyman continuum luminosities, the next nearest O stars are all capable of ionizing the gas along the line segment provided that a sufficient fraction of the ionizing flux is not absorbed by intervening H I.

The O7.5 giant ξ Per could account for the column density if 4% or more of the ionizing photons reach the distance (≈ 330 pc) of the line segment; a small additional flux, approximately 2% that from ξ Per, could be contributed by the three luminous B stars in the association, *o*, ϵ and ζ Per. Most of the ionizing radiation appears to be absorbed within about 90 pc of the stars by a small bright H II region, NGC 1499, about 1° north of ξ Per, by a fainter H II region, Sivan No. 4, which surrounds the association, and by an extended Hα halo (Reynolds 1988*b*). However, the possibility that some of the radiation penetrates to much larger distances along an H I free region between the star and the line segment cannot be ruled out.

The conclusions are similar for ζ Pup and δ Ori. The ionization could be produced by ζ Pup if about 2% or more of its ionizing photons are not absorbed by intervening H I. This corresponds to an optical depth $\tau < 4$ in the Lyman continuum or a total H I column density $N_{\rm H\,I} < 10^{18}$ cm^{-2}. Zeta Pup is the primary ionization source for the Gum nebula, a 250 pc diameter expanding shell that absorbs most of the star's ionizing flux (Reynolds 1976*a*, *b*). However, deep Hα photographs of the nebula by Chanot and Sivan (1983) show faint Hα emission extending outside the relatively bright shell, which suggests that some of the ionizing radiation does penetrate beyond the shell. And since ζ Pup (and δ Ori, see below) is located in a region of the Galactic disk that has extremely low H I column densities (Frisch and York 1983; Paresce 1984*a*), it is possible that a few percent of the ionizing radiation from the star or perhaps Lyman continuum photons produced by recombining hydrogen in the outer portions of the Gum nebula reaches the line segment. The O9.5 supergiant δ Ori is the western star in Orion's belt and a member of the Orion OB1 association. There is no detectable Hα intensity enhancement toward this star (Reynolds and Ogden 1979), indicating that very little of its large ionizing flux is absorbed in its immediate vicinity. Most of the flux from δ Ori and the other luminous stars in the association is absorbed within a very extended, shell-like structure, the Orion-Eridanus shell, surrounding the association (Reynolds and Ogden 1979). To account for the ionization along the line segment, at least 8% of δ Ori's or 2% of the association's flux must escape absorption along the 430 pc distance to the segment.

b) *Candidate Stars for the PSR 0823+26 Line Segment*

Figure 1*b* shows that only the O stars are potential sources of the ionization along the line segment to PSR 0823+26, even if θ Car and γ Cas have the earlier spectral types listed by Hoffleit (1982). The two nearest O stars, σ Sco and ζ Oph, can be ruled out because of their relatively low Lyman continuum luminosities and their unfavorable location with respect to the line segment (see Fig. 2*b*); the required ionizing fluxes are at least 10 times the fluxes emitted by the stars. On the other hand, the minimum fluxes required from ξ Per, ζ Pup, and Orion OB1 are 19%, 5%, and 17% the emitted fluxes, respectively. These stars are 300 to 400 pc from the line segment, and have measurable H I column densities of 1.2×10^{21}, 1.0×10^{20}, and 1.5×10^{20} (δ Ori), respectively. However, an H I free region with $N_{\rm H\,I} \lesssim 5 \times 10^{17}$ cm^{-2} between the line segment and one of these stars cannot be ruled out.

V. SUMMARY AND CONCLUSIONS

The line segments between the Sun and the two nearby pulsars PSR 0950+08 and PSR 0823+26 provide an excellent opportunity to investigate possible sources of the diffuse interstellar ionization revealed by the pulsar dispersion measures. The geometry of these two line segments and the locations and ionizing photon fluxes of the nearby luminous stars determine which stars are capable of producing the observed electron column densities along the line segments and what the sizes and densities of the associated H II regions must be.

From an examination of all the known ionizing stars in the vicinity of the line segments, it appears that only distant (>300–400 pc) O stars have Lyman continuum luminosities large enough to produce the observed column densities. The two B stars, α and β Cru, would be candidates for the ionization along the shorter PSR 0950+08 line segment, if the stars had ionizing photon luminosities at least 3–10 times larger (depending upon the geometry contrived for the H II regions) than the fluxes listed by Panagia (1973) for stars of their spectral types, and if the gas density were sufficiently low (<0.06 cm^{-3}) between the stars and the line segment 110–150 pc away. The Sco OB association, and, depending upon their spectral types, γ Cas and θ Car may have the minimum required ionizing luminosities for the PSR 0950+08 segment; however, associated H II regions near the stars and H I column densities suggest that a significant fraction of their ionizing photons never reach the line segment approximately 200 pc away.

The larger electron column density along the longer PSR 0823+26 line segment clearly cannot be produced by B stars, either individually or collectively (see Fig. 1*b*), or by the two nearest O stars. Moreover, since the PSR 0950+08 segment is never further than 60 pc from the longer PSR 0823+26 segment, it is likely that the lower column density of the PSR 0950+08 segment is just a consequence of its shorter length and the relatively large fraction of its length that is within the local X-ray emitting cavity. Thus the ionized gas toward PSR 0950+08 is probably much more extensive than that revealed by the pulsar's dispersion measure. This would make the requirements for the Lyman continuum luminosities of stars much higher for the PSR 0950+08 direction than the requirements actually used in Figure 1*a* and § IV, and therefore, would widen the gap between the luminosities that are required and the luminosities estimated from B star models. It appears that B stars could be a possible source of the ionization only if their actual Lyman continuum luminosities are more than an order of magnitude larger than the adopted model values. While there is some uncertainty about the correct temperature scale for B stars (e.g., Bochkarev 1987 and references therein), such a large discrepancy seems unlikely. Hot white dwarf stars are similarly ruled out. The ionization along the PSR 0823+26 segment would require, for example, at least 10 stars at the distance of HZ 43 ($\Delta = 58$ pc) that are $\sim 10^2$ times more luminous in the Lyman continuum than HZ 43 or 100 stars about as luminous as HZ 43 within 10 pc of the line segment (see Fig. 1*b*). Although knowledge of hot, evolved stars in the solar neighborhood is incomplete, such populations seem unlikely to have been missed. Also, Panagia and Terzian (1984) have estimated that the total production rate r of hydrogen ionizing photons by all white dwarfs is 1.6×10^{-16} s^{-1} cm^{-3}, which is $f/6$ the rate ($r = \alpha \langle n_e \rangle^2 / f$) required to sustain the ionized gas occupying a fraction f of the PSR 0823+26 segment; the mean value of f within the Galactic disk appears to be ~ 0.1 (e.g., Kulkarni and Heiles 1987; Reynolds 1977).

These conclusions for the PSR 0950+08 and PSR 0823+26 line segments in the solar neighborhood are similar to those reached about the diffuse, ionized gas within a much larger region of the Galactic disk from the study of the interstellar Hα background. Namely, O stars are the only known source of ionization with a Lyman continuum photon production rate that is sufficient to account for the mean hydrogen ionization rate within the diffuse interstellar medium ($\approx 4 \times 10^6$ s^{-1} per cm^2 of Galactic disk), but to account for the Hα background, especially at high latitudes, a significant fraction of the Lyman continuum photons must travel large distances from the stars (Reynolds 1984, 1987).

If O stars are the source of the ionization, the morphology of the interstellar gas must differ significantly from that usually depicted in models of the interstellar medium. In the McKee and Ostriker (1977) model, for example, the mean pathlength between the warm envelopes of H I clouds is only about 12 pc, and each envelope has an optical depth $\tau \approx 2$ for 20 eV photons; the mean pathlength between cold, totally opaque cloud cores is 88 pc. Such a distribution is clearly inconsistent with the requirements discussed above for O star ionization, which demand very extended ($\geq$300–400 pc) regions or channels, within which the gas has a density less than 0.1 cm^{-3} and is primarily ionized. A morphology in which the H I is confined to large sheetlike structures rather than to randomly distributed, spherical clouds may need to be considered. The Orion-Eridanus shell provides evidence that regions do in fact exist in which Lyman continuum photons travel freely over large distances. Portions of this photoionized shell extend 35°, corresponding to distances of about 250 pc, from the ionizing stars in the Orion OB1 association. The Gum nebula appears to have an interior cavity that is almost as large (Reynolds 1976*a*, *b*). There also is the 200 pc region of exceptionally low H I column density ($1.6 \pm 0.6 \times 10^{18}$ cm^{-2}) along the line to β CMa (Gry, York, and Vidal-Madjar 1985). Such structures, if pervasive, would be reminiscent of the original "tunnel" models of the interstellar medium by Cox and Smith (1974). More recently Cox (1989) has suggested a different picture in which a *warm*, "extracloud medium" occupies most of the interstellar volume. The diffuse ionization is then produced by O star photons that leak out between the clouds, creating extended channels of fully ionized gas through the warm medium, much like rays of sunlight through partial cloud cover.

The alternative to O star ionization requires the existence of a source of ionization that is more smoothly distributed within the Galactic disk than O stars and that has 10%–15% of the total ionizing power of the O stars. Thus the nature of the diffuse, ionized gas appears to have an important bearing on our understanding of the morphology of the interstellar medium and the principal sources of ionization and heating within it.

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REFERENCES

Ables, J. G., and Manchester, R. N. 1976, *Astr. Ap.*, **50**, 177.
Black, J. H., and Dalgarno, A. 1973, *Ap. J.* (*Letters*), **184**, L101.
Bochkarev, N. G. 1987, *Ap. Space Sci.*, **138**, 229.
Bohlin, R. C., Hill, J. K., Jenkins, E. B., Savage, B. D., Snow, T. P., Spitzer, L., Jr., and York, D. G. 1983, *Ap. J. Suppl.*, **51**, 277.
Bruhweiler, F. C., and Kondo, Y. 1982, *Ap. J.*, **259**, 232.
Celnik, W. E., and Weiland, H. 1988, *Astr. Ap.*, **192**, 316.
Chanot, A., and Sivan, J.-P. 1983, *Astr. Ap.*, **121**, 19.
Cox, D. P. 1989, in *IAU Colloquium 120, Structure and Dynamics of the Interstellar Medium*, ed. G. Tenorio-Tagle, M. Moles, and J. Melnick (New York: Springer), in press.
Cox, D. P., and Reynolds, R. J. 1987, *Ann. Rev. Astr. Ap.*, **25**, 303.
Cox, D. P., and Smith, B. W. 1974, *Ap. J.* (*Letters*), **189**, L105.
Cox, D. P., and Snowden, S. L. 1986, *Adv. Space Res.*, **6**, 97.
Craft, H. D. 1970, Cornell University, Center for Radiophysics and Space Research Rep. No. 395.
Frisch, P. C., and York, D. G. 1983, *Ap. J.* (*Letters*), **271**, L59.
Goldstein, S. J., Jr., and James, J. T. 1969, *Ap. J.* (*Letters*), **158**, L179.
Gry, C., York, D. G., and Vidal-Madjar, A. 1985, *Ap. J.*, **296**, 593.
Gwinn, C. R., Taylor, J. H., Weisberg, J. M., and Rawlings, L. A. 1986, *A.J.*, **91**, 338.
Hills, J. G. 1972, *Astr. Ap.*, **17**, 155.
Hoffleit, D. 1982, *The Bright Star Catalogue* (4th ed.; New Haven: Yale University Observatory).
Holberg, J. B. 1984, in *IAU Colloquium 81, Local Interstellar Medium*, ed. Y. Kondo, F. C. Bruhweiler, and B. D. Savage (NASA CP-2345), p. 91.
Kulkarni, S., and Heiles, C. 1987, in *Interstellar Processes*, ed. D. J. Hollenbach and H. A. Thronson, Jr. (Dordrecht: Reidel), p. 87.
———. 1988, in *Galactic and Extragalactic Radio Astronomy*, ed. G. L. Verschuur and K. Kellerman (2d ed.; New York: Springer), p. 95.
Lesh, J. R. 1968, *Ap. J. Suppl.*, **17**, 371.
———. 1972, *Astr. Ap. Suppl.*, **5**, 129.
Manchester, R. N. 1972, *Ap. J.*, **172**, 43.
———. 1974, *Ap. J.*, **188**, 637.
Manchester, R. N., and Taylor, J. H. 1977, *Pulsars* (San Francisco: Freeman).
———. 1981, *A.J.*, **86**, 1953.
Martin, P. G. 1988, *Ap. J. Suppl.*, **66**, 125.
McCook, G. P., and Sion, E. M. 1984, *A Catalogue of Spectroscopically Identified White Dwarfs* (Villanova Univ. Obs. Contr. No. 3) (Villanova: Villanova Press).
McKee, C. F., and Ostriker, J. P. 1977, *Ap. J.*, **218**, 148.
Morton, D. C. 1975, *Ap. J.*, **197**, 85.
Panagia, N. 1973, *A.J.*, **78**, 929.
Panagia, N., and Terzian, Y. 1984, *Ap. J.*, **287**, 315.
Paresce, F. 1984*a*, *A.J.*, **89**, 1022.
———. 1984*b*, in *IAU Colloquium 81, Local Interstellar Medium*, ed. Y. Kondo, F. C. Bruhweiler, and B. D. Savage (NASA CP-2345), p. 169.
Reynolds, R. J. 1976*a*, *Ap. J.*, **203**, 151.
———. 1976*b*, *Ap. J.*, **206**, 679.
———. 1977, *Ap. J.*, **216**, 433.
———. 1984, *Ap. J.*, **282**, 191.
———. 1985, *Ap. J.*, **294**, 256.
———. 1987, *Ap. J.*, **323**, 118.
———. 1988*a*, *Ap. J.*, **333**, 341.
———. 1988*b*, *A.J.*, **96**, 670.
———. 1989*a*, *Ap. J.* (*Letters*), **339**, L29.
———. 1989*b*, in *IAU Symposium 139, Galactic and Extragalactic Background Radiation*, ed. S. Bowyer and C. Leinert (Dordrecht: Reidel), in press.
Reynolds, R. J., and Ogden, P. M. 1979, *Ap. J.*, **229**, 942.
———. 1982, *A.J.*, **87**, 306.
Sanders, W. T., Kraushaar, W. L., Nousek, J. A., and Fried, P. M. 1977, *Ap. J.* (*Letters*), **217**, L87.
Schönberner, D., and Drilling, J. S. 1984, *Ap. J.*, **278**, 702.
Sivan, J.-P. 1974, *Astr. Ap. Suppl.*, **16**, 163.
Stokes, G. M. 1978, *Ap. J. Suppl.*, **36**, 115.
Weisberg, J. M., Boriakoff, V., and Rankin, J. 1979, *Astr. Ap.*, **77**, 204.
Wesemael, F., Green, R. F., and Liebert, J. 1985, *Ap. J. Suppl.*, **58**, 379.
Wray, J. D., Parsons, S. D., and Henize, K. G. 1979, *Ap. J.* (*Letters*), **234**, L187.

RONALD J. REYNOLDS: Department of Physics, University of Wisconsin, 1150 University Avenue, Madison, WI 53706