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AN ALMOST COMPLETE SURVEY OF 21 CENTIMETER LINE RADIATION FOR $|b| \geq 10°$. VI. ENERGETIC EXPANDING H I SHELLS

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ABSTRACT

H I, when viewed in narrow velocity ranges, is concentrated in arcs with typical diameters of tens of degrees. In some cases the diameters change with velocity in the manner expected for expanding shells. The clearest example appears to be consistent with a model involving an old supernova explosion. Much of the interstellar volume is probably contained within H I shells.

Subject headings: interstellar: matter — nebulae: supernova remnants — radio sources: 21 cm radiation

I. DATA

Figures 1 through 3 (Plates L4, L5, and L6) are photographs of H I in four small velocity ranges. The data are taken from the Hat Creek survey, and references to the fundamental details are given by Heiles and Jenkins (1976, Paper V). Figure 1 covers 17.9 to 21.1; Figure 2, 3.2 to 6.3; and Figure 3, −11.6 to −8.5 km s^{-1}. These particular photographs were selected from a complete set to show some individual H I structures. The other photographs contain many H I structures which are similar in appearance; we will publish the complete set, together with a detailed discussion, in the future.

The most striking feature in Figure 1 is the elliptically shaped closed ring centered near $l = 198°$, $b = -40°$. We believe that this ring is a section of an expanding H I shell, for two reasons. First, it changes in diameter with decreasing velocity—at first becoming larger as in Figure 2, then smaller as in Figure 3 where only a portion of the ring is discernible. For some velocities between those shown on Figures 2 and 3, it disappears. A perfect expanding shell would show disks at the extreme velocities at which the "caps" of the shell are approaching or receding, and rings of varying size for intermediate velocities. Second, there are other observational data which imply that an energetic event has disturbed the interstellar medium in this vicinity. These include the spectacular large arc-shaped filaments observed in Hα emission by Sivan (1974) and Reynolds, Roesler, and Scherb (1974); diffuse soft X-ray emission which is strongest near the center of the ring (Williamson *et al.* 1974; Naraman *et al.* 1976); and the star HD 28497 with significant O VI absorption (Jenkins and Meloy 1974). This object is the best example visible in the survey, and is discussed in more detail below. The denser parts of it appear as filaments which were previously studied by Verschuur (1973), who considered them to be part of supernova remnant.

Many similar structures exist, a few of which are visible in the photographs presented here. Even more are visible if the photographs are made with different "exposures." We believe that they are all parts of expanding shells, even though their correspondences with the model are much less nearly perfect. For example, some are not round, many do not change size smoothly with velocity, and most are discernible around only a portion of their complete (hypothesized) circumferences. Most are so large that we could not expect them to retain good symmetry during their voyage through the inhomogenous interstellar medium. We note that the Cygnus Loop and IC 443, which are widely accepted to be expanding shells on the basis of optical data, have significant structural irregularities. Shells of much smaller angular diameter have been previously observed around the supernova remnants HB 21 (Assousa and Erkes 1973) and W44 (Knapp and Kerr 1974), the Gum Nebula (Reynolds 1976*a*), and near $l = 165°$, $b = -18°$ (Sancisi 1973).

II. THE BEST EXAMPLE: PHYSICAL PROPERTIES

a) Distance

Optical interstellar absorption lines or the polarization of stars are the only distance indicators available. Unfortunately, in this vicinity there is no clear polarization pattern visible in the map of Mathewson and Ford (1970), and interstellar line data are meager.

HD 25558 ($l = 185°$, $b = -33°$, distance = 220 pc) has a Ca II line at +19.2 km s^{-1} (Ca II data quoted here are all from the summary of Habing 1969), a velocity which is located on the far wing of the H I profile at its position. This suggests that the positive-velocity portion of the shell—that portion receding from us, and farthest from us—is closer than 220 pc. HD 29248 ($l = 199°$, $b = -31°$, distance = 340 pc) and HD 34816 (λ Lep; $l = 215°$, $b = -26°$, distance = 540 pc) have Ca II lines at −12.6 and −14.9 km s^{-1}, respectively; these velocities are outside the main 21 cm profile and may imply that the negative-velocity portion is closer than 340 pc. On the other hand, HD 23793 ($l = 177°$, $b =$

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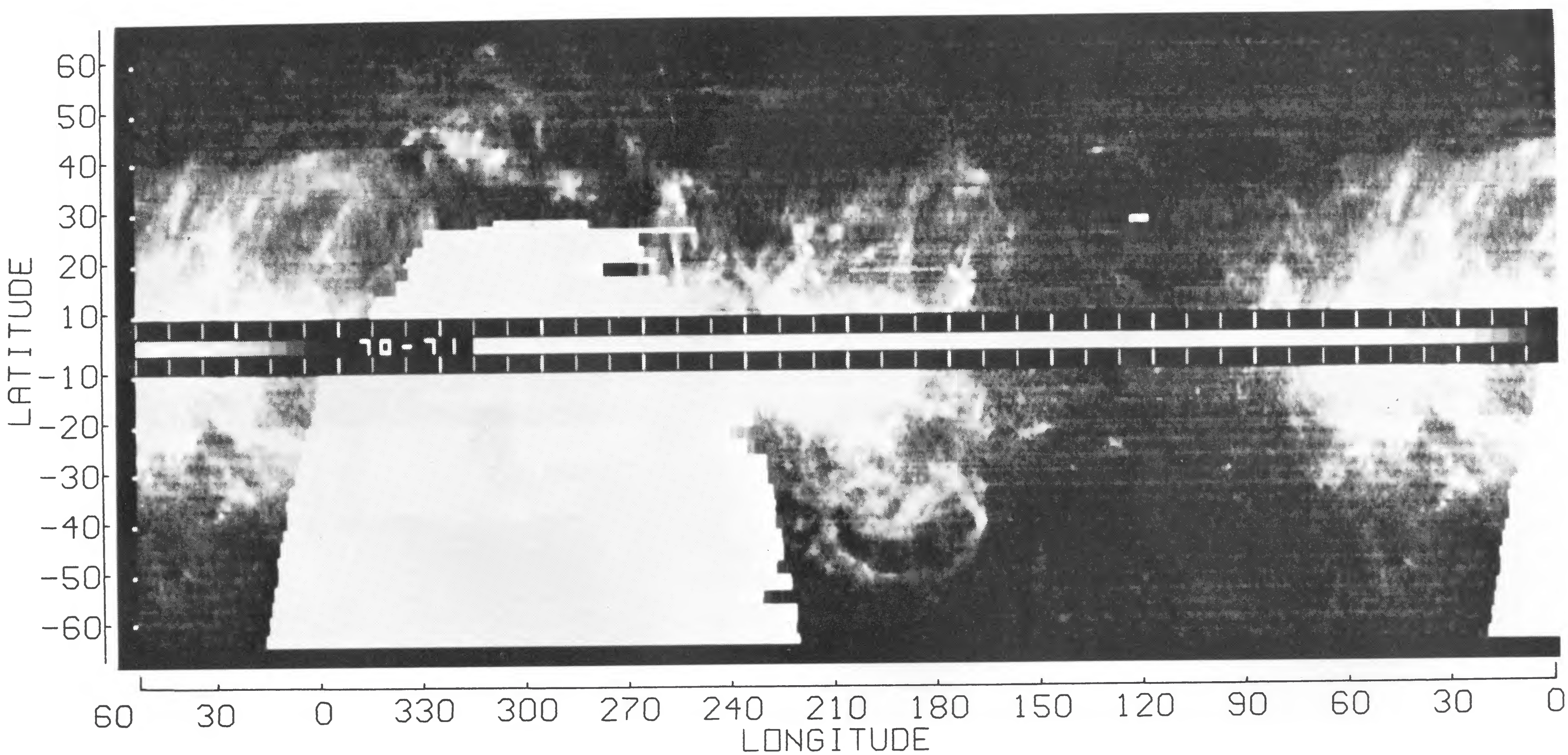

FIG. 1.—Photographic presentation of brightness temperature within the velocity range 17.9 to 21.1 km s^{-1} (LSR). White areas are brighter.

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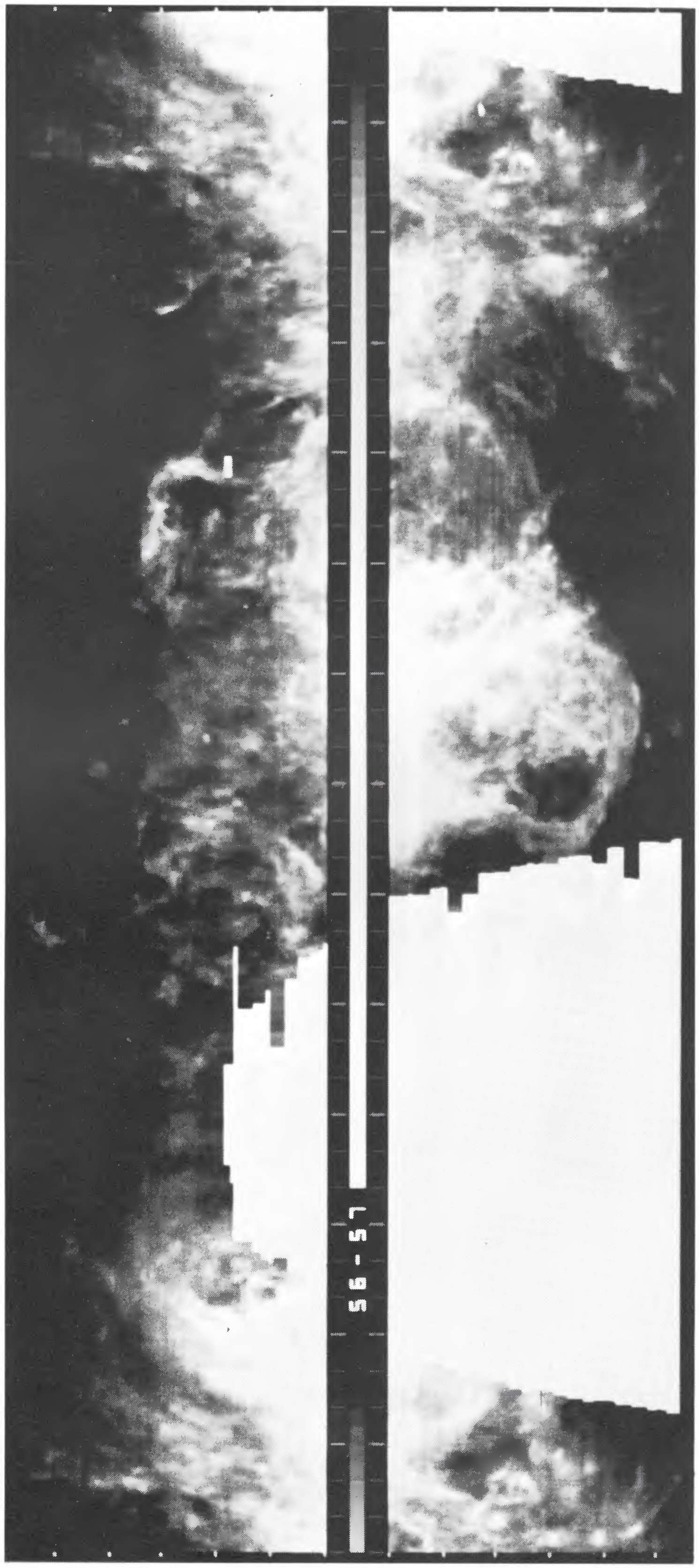

FIG. 2.—Same as Fig. 1, but for 3.2 to 6.3 km s^{-1}

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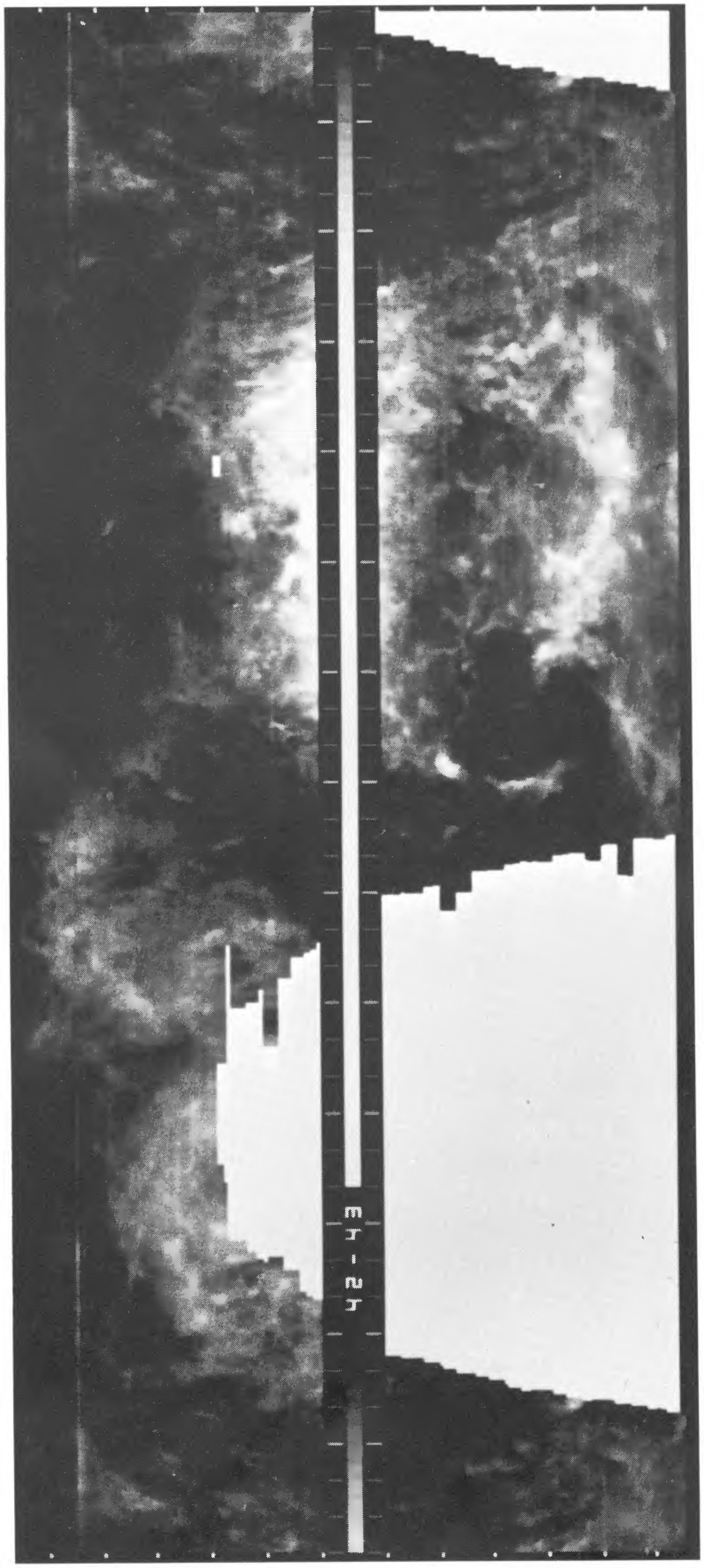

FIG. 3.—Same as Fig. 1, but for -11.6 to -8.5 km s^{-1}

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$-33°$, distance $= 210$ pc) has no Ca II lines corresponding to the H I velocities of the shell; and HD 29248 and HD 34816 have no negative-velocity lines corresponding to the H I shell velocities. It appears that Ca II lines are not necessarily a reliable indicator of shell material. Three other stars in the vicinity (but which are located farther from the center of the shell) with distances of 100–130 pc show no Ca II lines of anomalous velocity. In summary, if the Ca II data are relevant to the problem, they indicate that the distance of the far side of the shell is less than 220 pc, and that the near side is probably more distant than 130 pc.

Comparison of Lα and 21 cm column densities offers a reliable method to estimate distance, according to the recent reanalysis in Paper V. HD 34816 (Savage and Jenkins 1972), mentioned above, has a slightly larger column density in Lα than in 21 cm, which implies that the star is behind all of the gas, i.e., that the shell is closer than 540 pc.

The above information does not provide a definitive picture. We adopt—almost arbitrarily—a distance of 150 pc for the center of the shell. The distance dependence in our discussion below is expressed explicitly in terms of the parameter $d_{150} =$ (distance/150 pc). At a distance of 150 pc, the z-distance of the center is about 100 pc. This is not excessive. Much of the H I in this general direction is associated with the Orion and Perseus associations located 300–500 pc from the Sun; the H I extends to $b \approx -40°$, corresponding to a z-distance of about 250 pc.

b) *Mass, Energy, and Ambient Density*

The column density in the shell is difficult to estimate. In a particular direction on the sky some H I may not belong to the shell; and, owing to nonuniformities, different column densities characterize different positions on the shell. We take the position $l = 215°$, $b = -41°$ as representative. At this position, most of the H I seems to be associated with the shell. We estimate the observed contribution from the shell to be about 2.2×10^{20} cm^{-2}. Assuming the boundary of the shell at $b = -41°$ to occur at $l = 230°$ and the center at $l = 198°$, geometry reduces the column density in the radial direction to about 1.9×10^{20} cm^{-2}.

For purposes of estimating the volume, we take the angular radius equal to the geometric mean of the angular radii in the directions of l and b, about 19°. The corresponding linear radius is about 49 d_{150} pc. The total number of H I atoms swept up equals the column density in the radial direction multiplied by the area of the spherical shell, $5.5 \times 10^{61}\, d_{150}^2$ atoms, equivalent to $7.3 \times 10^4\, d_{150}^2\, M_\odot$ if elements other than H I are present in their normal abundances. If this mass had been distributed uniformly within the volume before the shell expanded, the H I density would have been $3.8\, d_{150}^{-1}$ cm^{-3}. Although the shell is visible over a range of about 40 km s^{-1}, the "caps" are not observed. From geometrical considerations we estimate the expansion velocity to be 23 km s^{-1}. Thus the total kinetic energy in the shell is about $3.8 \times 10^{50}\, d_{150}^2$ ergs.

III. THE BEST EXAMPLE: MODELS

The two models we consider involve shock fronts. We assume the shock velocity to equal the observed H I velocity, 23 km s^{-1}, since the shocks should be nearly isothermal.

a) *An Interstellar Bubble Blown by a Stellar Wind?*

Castor, McCray, and Weaver (1975) have shown that significant amounts of energy can be transferred to the interstellar medium by the energetic stellar winds which emanate from hot, evolved stars. Comparison of the observed radius and velocity with those predicted by the model allows us to specify the average energy loss rate dE/dt (units: $10^{-6}\, \dot{M}$ yr$^{-1} \times$ [2000 km s^{-1}]$^2 = 325\, L_\odot$), and the length of time the process has been occurring t_6 (units: 10^6 years). The results are: $dE/dt = 32.0 d_{150}$; $t_6 = 1.25 d_{150}$. The units of dE/dt were chosen by Castor, McCray, and Weaver (1975) to correspond roughly to the observed value for the O5f star ζ Pup (Morton, Jenkins, and Brooks 1969; Smith 1970), which is lower by a factor of up to 10 than a wider sample selected for large mass-loss rates (Hutchings 1976). The only reasonable candidate from the Bright Star Catalog is HD 29248, a B2 III star mentioned above. Although this star is located very close to the center of our shell, its distance of 350 pc would more than double the required energy input rate, probably making the energy requirements too severe.

b) *An Old Supernova Explosion?*

In the later stages of a supernova explosion the adiabatic Sedov solution (see Cox 1972) reverts to an approximate momentum-conserving ("snowplow") solution in which the radius varies approximately as $t^{0.31}$ (Chevalier 1974). In these stages the pressure of the hot gas in the interior should be considerably less than the ram pressure of the shell against the ambient medium; the physical parameters for the interior, derived by Naranan *et al.* (1976) from X-ray and O VI data, bear this out. Chevalier has also given an interpolation formula from which we can obtain the original energy of the explosion E_0. Applying these gives $t_6 = 0.65 d_{150}$, $E_0 = 3.6 \times 10^{51} d_{150}^2$ ergs, with the kinetic energy of the shell at present comprising about 11 percent of E_0. Our value of E_0 is close to the value 5×10^{51} ergs deduced by Reynolds (1976*b*), using Chevalier's models, for the shell observed in the Gum Nebula (Reynolds 1976*a*). Expected values for E_0 are not highly certain and probably vary quite widely, as shown by the following examples (Shklovsky 1968): Cas A, 5×10^{50} ergs; N49 in the Large Magellanic Cloud, 10^{52} ergs; Type III supernovae, 10^{53} to 10^{54} ergs. It appears that the energy requirements for this model are large, but not unreasonable.

IV. CONCLUDING REMARKS

The number of shells visible in the complete set of photographs is large. Nearly every H I density concentration appears to be part of a large arc and therefore an expanding shell in the present interpretation. It is

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our impression that much of the interstellar volume is contained within these shells, in much the same way as envisioned by Cox and Smith (1974). The existence of shells or sheets of interstellar gas has previously been deduced by many techniques including optical (Herbig 1968; Morton 1975), radio (Heiles 1967; also the supernova shells referenced above in § I), and ultraviolet studies of H_2 (Hollenbach, Chu, and McCray 1976). With the wide distribution of expansion velocities, optical or radio spectra of shells taken at individual points on the sky can probably be interpreted as consistent with the concept of "interstellar clouds," a concept which is misleading because clouds as roughly spherical self-contained entities are rare.

The models presented in § III are not really consistent with this picture, because they assume a uniform medium extending over a large volume. There are two simple departures from this idealization. In one, the original gas cloud is very much smaller and denser; after the shock reached the edge of the cloud, the shell would presumably travel nearly unimpeded through the low-density "intercloud medium." Another, whose theoretical treatment has been only briefly discussed by Chevalier (1974), is a supernova explosion which has occurred inside an existing cavity. A cavity would be expected if the star were massive and had a significant stellar wind before its explosion. Alternatively, or in addition, it is not unlikely for a supernova to be located inside a cavity created by previous supernovae—particularly since Type II supernovae result from young stars which tend to be formed in clusters.

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