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DETECTION IN Hα OF A SUPERSHELL ASSOCIATED WITH W4

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ABSTRACT

From H I observations, Normandeau, Taylor, & Dewdney have identified a possible Galactic chimney emanating from W4. We observed a 10° diameter field centered on this region in the Hα line using a CCD camera sensitive to faint extended emission. Our image shows an apparent shell of H II, which we interpret as the ionized inner wall of a superbubble produced by stellar winds from the very young star cluster OCl 352. An analysis of the ionization balance indicates that much of the Lyman continuum radiation from the star cluster is absorbed and does not escape from the disk. The shell appears to close 6° (or about 230 pc) above the star cluster, and at a Galactic latitude of 7°. The shell is quite elongated, with its major axis approximately perpendicular to the Galactic plane, as predicted for a superbubble formed in a stratified Galactic disk. The large size of the shell leads to an estimated age between 6.4 and 9.6 Myr, which exceeds that of OCl 352 ($\lesssim$2.5 Myr). The reason for this discrepancy is unclear, although it is possible that an earlier epoch of stellar outflow has contributed to the growth of the W4 superbubble.

Subject headings: Galaxy: structure — ISM: bubbles — ISM: individual (W4 Supershell) — ISM: structure — supernova remnants

1. INTRODUCTION

O and B stars play an important role in shaping the structure of the interstellar medium. Most importantly, stellar winds and supernovae from OB associations are thought to create large bubbles of rare, hot gas surrounded by shells of cooler gas "snowplowed" by these outflows (Weaver et al. 1977). Manifestations of these phenomena include H I observations of numerous shells in our Galaxy (Heiles 1979, 1984), soft X-ray observations of the hot ($\approx 10^6$ K) gas within bubbles (Cash et al. 1980), and some line emission observations (most notably Hα) of gas in shells phototoionized by the remaining O stars within the association (Reynolds & Ogden 1979).

Several groups (Tomisaka & Ikeuchi 1986; Mac Low & McCray 1988; Mac Low, McCray, & Norman 1989) have predicted that the more energetic bubbles should break through the gas layer of the Galactic disk, forming Galactic "chimneys" that transport hot gas to the Galactic halo (Norman & Ikeuchi 1989). Such chimneys are thought to play a key role in maintaining the halo. C. Heiles and coworkers (Heiles 1979; Koo, Heiles, & Reach 1992) identified vertical structures seen in H I observations, "worms," that could represent the walls of chimneys. Holes in the surface distribution of H I in other galaxies (Brinks & Bajaja 1986; Deul & den Hartog 1990) may be sites where bubbles have broken through the gas layer, becoming, in effect, chimneys. Besides conveying hot gas to the halo, chimneys may provide a channel for Lyman continuum photons from O stars in the disk to reach the diffuse, ionized medium (Dove & Shull 1994), the "Reynolds layer" (Reynolds 1991). The mechanism for ionizing this layer is not well understood (Reynolds & Tufte 1995), and it is important to determine the global fraction of O star radiation reaching it.

Observations of a well-resolved Galactic chimney have remained elusive. Recently, however, Normandeau, Taylor & Dewdney (1996, hereafter NTD) observed a conical cavity in H I above the very young open cluster OCl 352 (Mel 15), which is associated with the H II region W4. The cavity showed evidence of energetic outflow, such as gas apparently swept back from small entrained molecular clouds, which NTD suggested was caused by winds from the O stars in OCl 352. The cone appeared open, and NTD interpreted this structure as a Galactic chimney.

We observed this region (which includes the extended Cas OB6 association) in Hα with the Virginia Tech Spectral Line Imaging Camera (SLIC), which produces highly sensitive images over large fields ($\approx$10°). Our observations trace the ionized walls of the cavity that appear to close about 6° above the star cluster.

2. OBSERVATIONS AND IMAGE REDUCTION

The SLIC uses a narrow bandpass Hα interference filter placed in front of a cryogenically cooled TK 512 × 512 CCD camera with 27 μm pixels in the focal plane of a fast (f/1.2) Noct-Nikkor lens. The 58 mm focal length yields a pixel size of 1.′6. A filter wheel in front of the lens permits imaging with either a narrow bandpass Hα interference filter (6566 Å center wavelength and 17.5 Å bandpass) or a wider bandpass interference filter (6083 Å center wavelength and 80 Å bandpass) in a line-free part of the spectrum. Tracking to arcsecond precision is achieved through the use of a separate auto-tracking CCD camera. The system is located at a dark site at the Horton Research Center in southwestern Virginia.

On the night of 1995 October 17, we obtained twelve 10 minute Hα images and a 5 minute continuum image of the region in Cassiopeia centered on $\alpha = 02^{\rm h}46^{\rm m}$, $\delta = +63°30'$ (2000.0). Our 10° image was wide enough so that W3, W4, and W5 were in the field of view. We recorded 10 flat-field images for each filter. Since the images are wide, normal sky flats or dome flats will not work. Instead, we used a flat-field box described elsewhere (Simonetti, Dennison, & Topasna 1996). In addition, we recorded 10 zero-integration bias images. Due to the very low dark current of the system (≈0.001 electrons s^{-1} $pixel^{-1}$), "dark" images were not necessary.

Image processing was performed using IRAF.[1] Using averaged bias and flat-field images, we corrected each of the 10 minute Hα images. These corrected images were then averaged to produce a single Hα image. All averaging procedures ignored the highest pixel value at each pixel location, thus removing any cosmic-ray defects.

The center bandpass of the interference filter shifts toward shorter wavelengths with increasing off-axis angle. As a result, sensitivity to Hα declines sharply beyond 5°, limiting the usable field diameter to 10°. Our images show minor contamination from atmospheric OH emission, specifically the (6–1) $P_1(3)$ line at 6553.7 Å (Chamberlain 1961). The shortward shift of the bandpass with off-axis angle results in increasing sensitivity to the OH(6–1) $P_1(3)$ line with angle, particularly beyond 4°. This, combined with the falloff in sensitivity to the otherwise uniform geocoronal Hα emission beyond 5°, yields the appearance of a faint ring of radius ≈5°. This ring is consistently present in Hα images in any direction and is uniform because sidereal tracking over the 2 hr period has smoothed out any spatial structure in the OH line. This background was removed by subtracting a ring with Gaussian radial dependence, peaking at 4°.96. The W4 Hα shell discussed below was not coincident with the ring, and was readily apparent and distinct from the ring in the raw images.

In order to convert pixel values in the Hα image to rayleighs, we used the Hα fluxes of the planetary nebulae IC 289, IC 1747, NGC 650-1 (M76), and NGC 7027, determined from Cahn, Kaler, & Stanghellini (1992) (1 rayleigh [R] = $10^6/4\pi$ photons cm^{-2} s^{-1} sr^{-1}). IC 289 and IC 1747 were in the image. We took a 5 minute Hα image of NGC 7027 and two 5 minute Hα images of NGC 650-1. The internal consistency among the four calibrators is 6% rms.

The rms fluctuation in areas of the final image without obvious structure or individual stars is 0.8 R $pixel^{-1}$. This noise level represents a confusion limit at low Galactic latitude set by faint, unresolved stars.

3. RESULTS

The final image is shown in Figures 1 and 2 (Plates L3 and L4). The three bright H II regions, W3 (IC 1795), W4 (IC 1805), and W5 (IC 1848), are readily visible. OCl 352 (indicated by "SC" in Fig. 2) is at a Galactic latitude of 0°.9. It contains nine O stars that are responsible for the ionization of W4. The complex structure of W4 is evidently due to the effects of outflow from OCl 352.

Extending above the plane and away from W4, we trace filaments of ionized gas that close apparently 6° above OCl 352, corresponding to an extent of 230 pc at the adopted distance of 2.2 kpc to this region (Humphreys 1978). Other Hα observations confirm the existence of this faint emission (McCullough, Reach, & Treffers 1990; T. Reddmann 1996, private communication). The lower parts of these filaments closely outline the perimeter of the H I cavity reported by NTD. We thus interpret this large Hα loop as the ionized wall of a shell enclosing a superbubble produced by energetic outflows from the star cluster. The brighter parts of the shell at low Galactic latitude agree well with radio continuum observations reported by NTD and with the Palomar Sky Survey E plates, both of which have lower sensitivity to emission measure. NTD also interpreted the bright filament extending upward from the eastern side of W4 as the ionized wall of the cavity; our observations trace the full extent of this cavity. The shell is a very faint structure. Table 1 gives some observed values of the Hα surface brightness at various locations within the shell. Although the surface brightness in the faintest parts of the shell (at position I, for example) is comparable to the sensitivity, even these parts are readily detectable because the shell is more than 10 pixels thick and many more pixels in length. The thickness of the ionized shell varies from about 0°.2 to about 0°.5.

TABLE 1

Hα INTENSITIES IN THE W4 SHELL

Location	Intensity (R)
A	500
B	190
C	190
D	250
E	340
F	91
G	29
H	6.7
I	0.7
J	2.7
K	5.8
L	2.8
M	39
N	36
O	310

Below OCl 352, and toward the Galactic plane, the outflow has apparently produced a small cavity that we see outlined by intense Hα emission. In this direction, the flow has rammed into dense molecular gas (Digel et al. 1996), most likely remnants of the cloud from which OCl 352 formed. The lower ring of bright Hα emission corresponds with the edge of an arc of CO emission seen by Digel et al., and clearly represents gas heated and photoionized by the UV radiation from OCl 352.

The W4 Supershell is in some respects similar to the Aquila Supershell recently mapped in H I (Maciejewski et al. 1996). From a conical base, it extends about 550 pc below the Galactic plane where it appears to close in a broad shell.

4. DISCUSSION

4.1. *Photoionization*

Here we examine photoionization of the W4 Supershell by the stars in OCl 352. If no Lyman continuum photons escape from the region, photoionization equilibrium is described by the following equation:

$$Q\frac{d\Omega}{4\pi} = \frac{1}{3}R_1^3\,\alpha_A(T_1)n_1^2\;d\Omega + r^2\alpha_B(T)n^2 s\;d\Omega\,. \qquad (1)$$

The left-hand side of equation (1) represents the number of Lyman continuum photons emitted per second into solid angle $d\Omega$. The first term on the right accounts for the rate of photon absorption in the small, compact H II region (with radius R_1, density n_1, and temperature T_1) that is cospatial with the star cluster. In our image, this appears as a bright knot of Hα emission at the location of the star cluster (position "SC" in Fig. 2). The second term then corresponds to the shell that has

[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

density n, thickness s, and temperature T, and that is located at distance r from OCl 352. The recombination coefficients appropriate to optically thin and thick regions are $\alpha_A(T_1)$ and $\alpha_B(T)$ (Osterbrock 1989). From the tabulation of nine O stars within OCl 352 (NTD), we estimate that $Q \approx 2.3 \times 10^{50}$ s^{-1} using Panagia (1973). We shall use equation (1) to predict Hα surface brightnesses to be compared with the observed values.

We estimate the magnitude of the first term on the right in equation (1) by integrating the Hα surface brightness over the compact H II region (at SC). This is then corrected for both extinction and continuum radiation from stars. (The extinction at Hα is 2.1 mag, after adjusting the average V-band extinction to the stars in OCl 352 [Humphreys 1978]. The continuum contribution is determined from the continuum image.) The resulting Hα flux is proportional to the volume emission measure EM_V, given by

$$\mathrm{EM}_V = \int \mathrm{EM}\, dA = \frac{4\pi}{3} n_1^2 R_1^3 \,, \qquad (2)$$

where A is the projected area at the H II region. The line-of-sight emission measure EM is proportional to the Hα surface brightness, and for $T_1 = 10^4$ K, a surface brightness of 1 R corresponds to EM = 2.8 pc cm^{-6}. We obtain

$$\frac{4\pi}{3} n_1^2 R_1^3 \alpha_A(T_1 = 10^4 \text{ K}) \approx 1.6 \times 10^{49} \text{ s}^{-1} . \qquad (3)$$

Direct comparison with Q then indicates that only about 7% of the ionizing radiation from OCl 352 is absorbed by the compact H II region at SC.

The factor $n^2 s = \mathrm{EM}_\perp$ in the second term on the right in equation (1) represents the emission measure along a path perpendicular to the shell. Since we are apparently seeing an edge-brightened shell, the maximum emission measure seen at the edge should be $\mathrm{EM}_s = \mathrm{EM}_\perp[1 + (2r/s)]^{1/2}$ for spherical geometry. We measure $r/s \approx 12$, and thus $\mathrm{EM}_s \approx 5\, \mathrm{EM}_\perp$. For the large shell above OCl 352, equation (1) would predict that $\mathrm{EM}_s \approx 210$ pc cm^{-6} at $r \approx 230$ pc, corresponding to the outermost part of the shell. If we assume $T = 10^4$ K, and that the extinction to the shell is negligible at this Galactic latitude (7°), then the Hα surface brightness implied by equation (1) is ≈76 R, well in excess of that observed. An upper limit to the extinction to the upper shell can be estimated by assuming that all of the 100 μm emission in the *IRAS* maps in this direction occurs in front of the shell. In this case, the Hα surface brightness is reduced to ≈20 R, still well above the values observed in the outer shell (positions H through K in Fig. 2 and Table 1). In addition, since $\mathrm{EM}_\perp \gtrsim 40$ pc cm^{-6}, we should expect to detect the shell along lines of sight through the middle and not just on the edges.

A similar analysis can be applied to the much smaller shell of Hα emission below OCl 352, in which virtually all ionizing radiation must be stopped by the high column density of gas in this region. In this case, equation (1) predicts $\mathrm{EM}_s \approx 7400$ pc cm^{-6}. In this direction, the extinction must be at least 2.1 mag toward the star cluster, and thus the predicted surface brightness is ≈370 R. Given the uncertainties in Q, and the extinction toward the lower shell, we regard the observed surface brightness at positions C and D (≈200–250 R) to be in good agreement.

The apparent deficiency in emission measure in the large upper shell can be accounted for by the presence of two small molecular clouds (Digel et al. 1996) apparently within the bubble and quite near OCl 352. These clouds show evidence of ablation and acceleration by the stellar winds emerging from the star cluster (NTD). NTD point out that the cloud nearer the cluster subtends a solid angle of 6.2×10^{-2} sr as seen from OCl 352, corresponding to an angular diameter of 16°. Immediately below these clouds at position O, we see a small Hα filament parallel to the Galactic plane that we interpret as the expected ionization layer between the molecular gas and the intense radiation field from the star cluster. (See Heyer et al. 1996 for a similar interpretation and detailed discussion of the molecular gas.) Modeling this filament as having a thickness along the line of sight equal to its width on the sky, equation (1) predicts a maximum emission measure through the filament of 1.2×10^4 pc cm^{-6}. This corresponds to an expected peak surface brightness of 600 R, when the extinction (2.1 mag) is included. This is in reasonably good agreement with the observed peak brightness in this filament (≈300 R), given the various modeling uncertainties, especially the thickness of the filament. We thus conclude that much of the upper shell is significantly shadowed by the small molecular clouds relatively near OCl 352. The emission measure seemingly missing from the large upper shell is then found in this filament on or near the lower surfaces of these clouds.

We note that the surface brightness predicted using equation (1) exceeds that observed by about a factor of 2 for both the filament and the lower shell. This may indicate that the value of Q is overestimated or that the extinction has been underestimated. In any case, the lower shell is almost certainly ionization bounded. If we then use the lower shell as a predictor of the amount of ionization above OCl 352, we conclude that much of the upward-directed ionizing radiation is captured and does not escape from the disk.

4.2. *Dynamics*

The elongated shape of the shell is similar to that expected for expansion into a stratified atmosphere (Tomisaka & Ikeuchi 1986; Mac Low & McCray 1988; Mac Low et al. 1989). Mac Low & McCray (1988) define a dynamical timescale characteristic of the time required for a bubble to expand to 1 scale height, H. This timescale can be written as

$$t_D = 1.25 \text{ Myr} \left(\frac{H}{100 \text{ pc}}\right)^{5/3} \left(\frac{n_0}{L_{38}}\right)^{1/3} , \qquad (4)$$

where L_{38} is the mechanical luminosity in units of 10^{38} ergs s^{-1}, and n_0 is the ambient density of hydrogen in atoms cm^{-3} in the Galactic plane. In addition, they define a dimensionless dynamical parameter that determines whether a bubble will blow out of the disk. This can be written as

$$D = 940 L_{38} \left(\frac{H}{100 \text{ pc}}\right)^{-2} n_0^{-1} , \qquad (5)$$

for an ambient temperature $T = 10^4$ K. In both expressions, we assume a mean atomic mass of $\mu = 1.3$. NTD estimate that $L_{38} \approx 0.3$ based upon the wind energy expected from the O star content of OCl 352. They also estimate $n_0 \approx 5$ cm^{-3} from adjacent H I observations. This gives $t_D \approx 3.2$ Myr and $D \approx 60$ for $H = 100$ pc. The time required for the W4 superbubble to expand from the 35 pc height of OCl 352 to 2.3 scale heights (as suggested by the 230 pc height of the shell) is between $2t_D$ and $3t_D$, or 6.4–9.6 Myr. The estimated value of

D suggests that the superbubble may be marginally able to break out from the disk, since breakout occurs in simulations with $D \gtrsim 10^2$ (Mac Low & McCray 1988; Mac Low et al. 1989).

The estimated age of the W4 superbubble is significantly larger than that of OCl 352. The age of the cluster has been variously estimated as 1.3 Myr (Harris 1976), between 1 and 2 Myr (Moffat 1972), between 2 and 2.5 Myr (Llorente de Andrès, Burki, & Ruiz del Arbol 1982), and $\leq$2.5 Myr (Mathys 1987). Evidently, few if any stars have evolved to the supernova stage, and thus stellar winds appear to be the primary agent for forming the superbubble, much as NTD suggest. It is also possible that an earlier epoch of massive star formation in the molecular cloud complex just south of W4, with subsequent outflowing winds and supernova explosions, has contributed to the W4 superbubble. The rather remarkable alignment of the supershell with OCl 352 suggests, however, that OCl 352 is in fact the dominant contributor. A reasonable scenario may involve a region of reduced density left by outflows from earlier stellar activity, which the W4 superbubble has entered.

We also note that a lower ambient density could reduce the apparent age of the superbubble. This might be the case if the density estimated by NTD has been enhanced by gas pushed outward as the superbubble formed. If, for example, $n_0 \approx 1$ cm^{-3}, then the estimated age of the superbubble is between 3.7 and 5.6 Myr. Even in this case, the apparent age of the W4 superbubble exceeds the age of OCl 352.

5. CONCLUSIONS

Hα observations reveal the ionized wall of an apparently closed superbubble above the star cluster OCl 352 in the region of the Cas OB6 association. The emission measure associated with surfaces exposed to the star cluster is in approximate accord with that expected. We conclude, therefore, that much of the ionizing radiation does not escape from the disk.

This object is elongated as expected for a superbubble forming in a stratified medium. The age of the superbubble appears to be greater than that of this very young star cluster. H I observations of the surrounding gas, as well as X-ray observations of the hot gas within the superbubble, will be critical for a better determination of its properties. In addition, numerical models with parameters specific to this case are urgently needed to better determine the dynamics and age.

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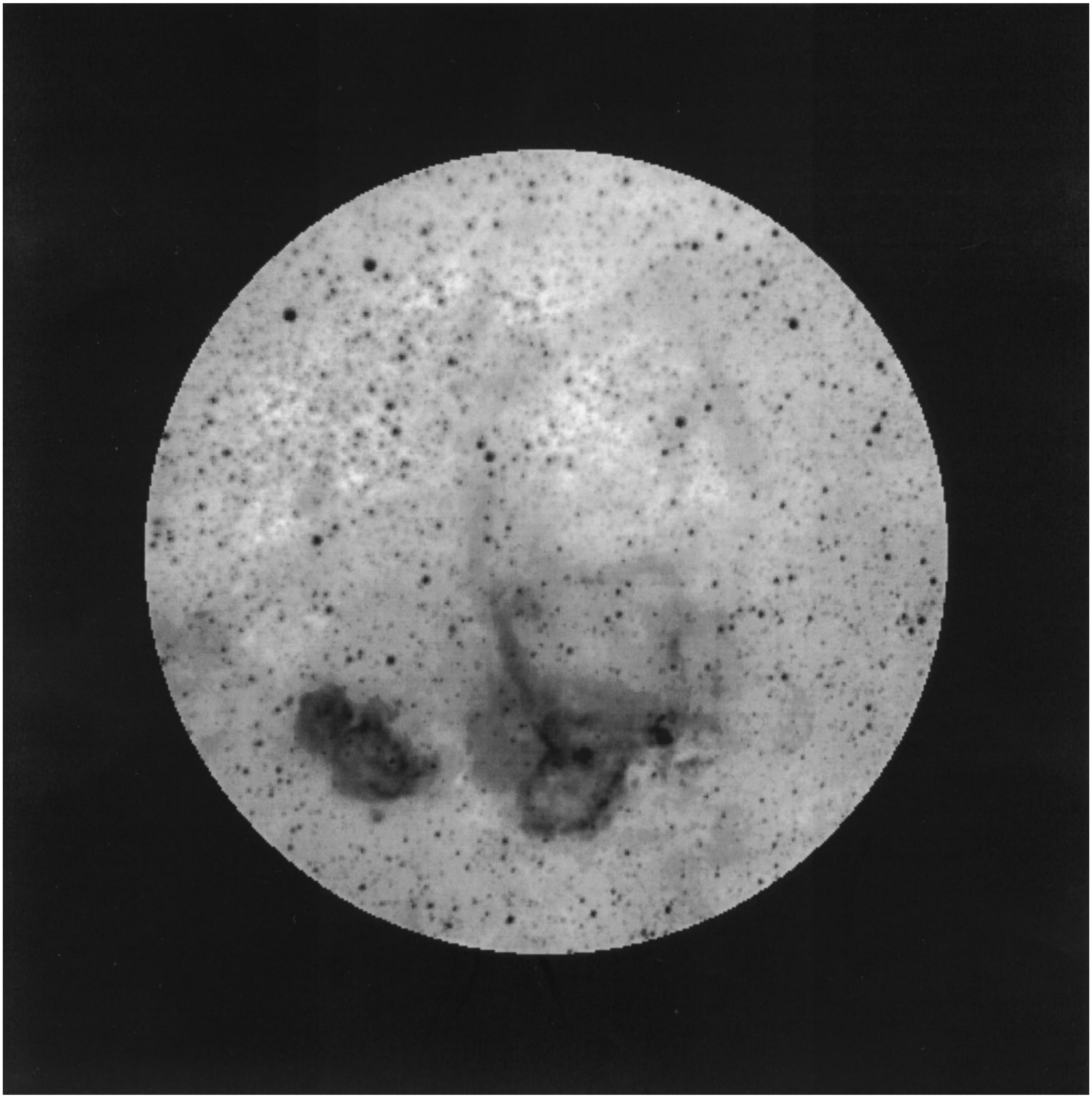

FIG. 1.—The W4 Hα Supershell (negative image). To encompass the large dynamic range of the surface brightness, we display (surface brightness)$^{0.2}$.

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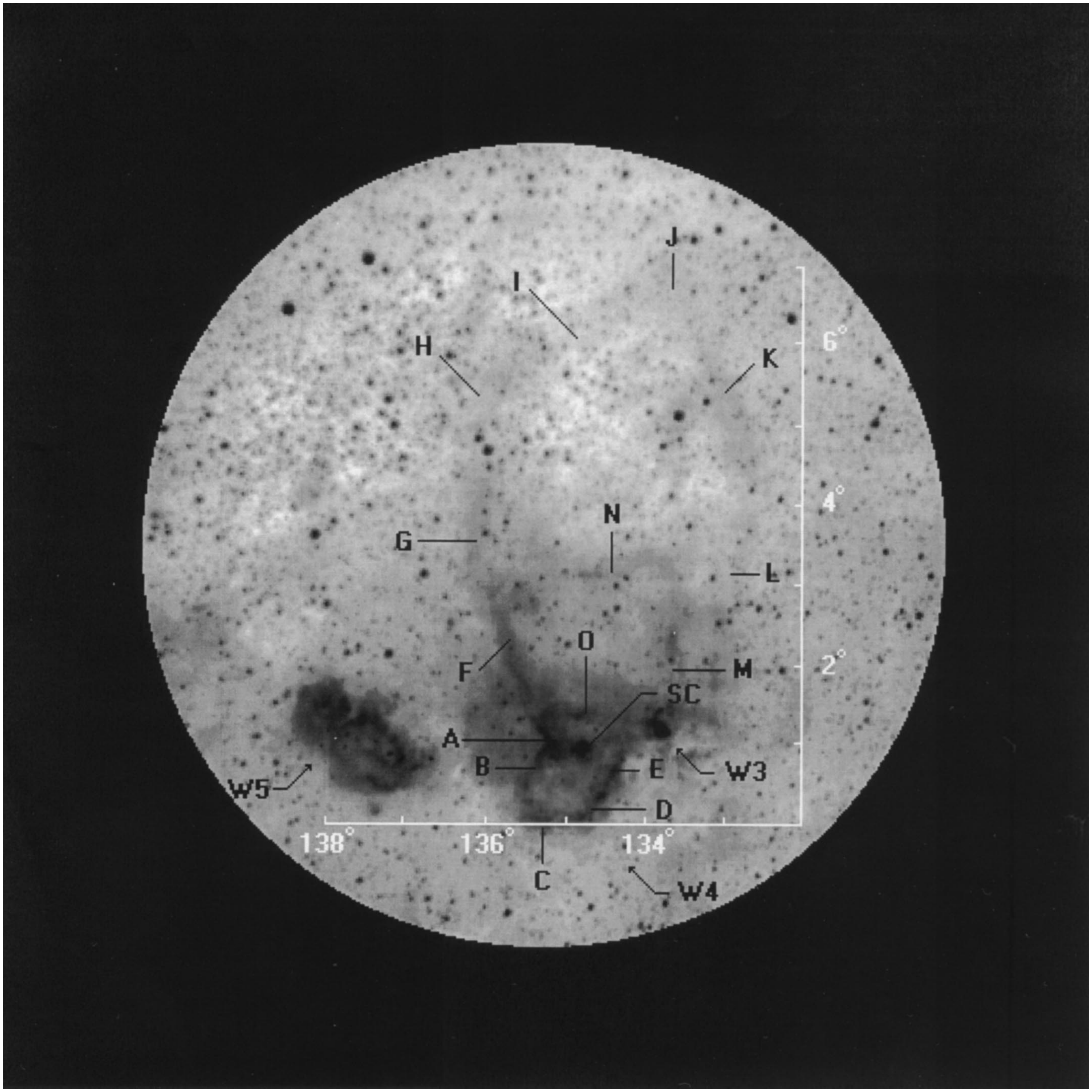

FIG. 2.—Index to locations in the W4 Hα Supershell. W4 is ionized by UV radiation from the star cluster OCl 352 embedded in strong Hα emission at SC. The complex structure of W4 is due to outflow from the star cluster. This includes a large superbubble extending upward to a Galactic latitude of 7°, and outlined by a shell of Hα emission (F through M). A much smaller shell (B through E) extending downward toward the Galactic plane evidently indicates the boundary between the bubble and the dense molecular gas. The Hα surface brightness at positions A through O are given in Table 1. Galactic coordinates are shown. Image is the same as Fig. 1.

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