The Astronomical Journal, 126:1925–1932, 2003 October

FRAGMENTATION OF GLOBULES IN H II REGIONS: *HUBBLE SPACE TELESCOPE* IMAGES OF THACKERAY'S GLOBULES

Bo Reipurth,[1] Alex Raga,[2] and Steve Heathcote[3]
Received 2003 June 6; accepted 2003 July 9

ABSTRACT

We present *Hubble Space Telescope* WFPC2 images through an Hα filter of Thackeray's globules in the southern H II region IC 2944. The images document the state of the globule complex during its current highly dynamical phase of breakup. A population of very small and short-lived splinters suggests that continuous fragmentation must play an important role in increasing the surface-to-mass ratio of the neutral gas, thus accelerating the processes of photoevaporation and photoablation. We are not able to single out which of various theoretical mechanisms for breakup is operating in the globule complex.

Key words: dust, extinction — H II regions — ISM: clouds — ISM: globules — ISM: kinematics and dynamics

1. INTRODUCTION

The ultraviolet radiation from young OB stars still associated with their birthplaces drives a wealth of radiative and dynamical processes in H II regions. Of particular interest are the interfaces between neutral and ionized matter, in which photoevaporative flows are set up. Numerous studies have dealt with photoevaporation of neutral material by ultraviolet radiation, and the basic processes are well understood (e.g., Oort & Spitzer 1955; Bertoldi 1989).

Photographs and wide-field images of H II regions often show small and isolated dark globules within the luminous gasses. Attention was first drawn to these by Bok & Reilly (1947), and later a tear-shaped variant was discussed by Herbig (1974). Although such small dense globules are subjected to powerful UV radiation, they do not evaporate instantly. This is because an ionization-shock front is set up at the interface between neutral and ionized material, and recombination in the downflow region shields the globule from almost all of the incident UV radiation. Therefore, the front will move only very slowly into the globule, which in principle could survive for long periods of time (e.g., Kahn 1969; Dyson 1973; Tenorio-Tagle 1977).

However, this assumes that the globule remains intact and more or less spherical. Examination of globules shows that this is often not the case. Indeed, dynamical processes appear to exist that fragment globules into smaller splinters. Such small pieces have a much larger surface-to-volume ratio than the original globule and are therefore much more sensitive to evaporation (Reipurth 1983). In this study we examine fragmentation in a system of globules in the southern H II region IC 2944.

[1] Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822; reipurth@ifa.hawaii.edu.

[2] Instituto de Ciencias Nucleares, Universidad Nacional Autonoma de México, Apdo. Postal 70-543, 04510 México, D. F., Mexico (raga@astroscu.unam.mx).

[3] Southern Astrophysical Research Telescope, Casilla 603, La Serena, Chile (sheathcote@ctio.noao.edu).

2. OBSERVATIONS

The observations were made on 1999 February 7 using WFPC2 onboard the *Hubble Space Telescope*[4] through an Hα (F656N) filter. WFPC2 contains four CCDs, imaged with different cameras. Three of the cameras, referred to as the Wide Field Cameras (WF2–WF4) image the focal plane at a scale of $\sim$0."1 pixel^{-1}. The other, called the Planetary Camera (PC1), provides a scale $\sim$0."046 pixel^{-1}. Each WF CCD has a field of 80" by 80", and at the distance of 1.8 kpc the 0."1 pixel^{-1} scale corresponds to 180 AU per pixel. A total of eight exposures were made, each of 160 s. Additional brief exposures were obtained in broadband *B*, *V*, *R* filters by the *HST* Heritage Team and were used with the deep Hα exposure to produce the color figure in Figure 1.

3. THE COMPLEX OF THACKERAY'S GLOBULES

3.1. *Earlier Work on Thackeray's Globules*

Thackeray (1950) discovered a small complex of globules in the southern H II region IC 2944. The main O star in this H II region is a sixth magnitude O7 III star, HD 101205 (Walborn 1973, 1987). Other O stars are located within the boundaries of the H II region, and Thackeray & Wesselink (1965) suggested a distance for them of 2 kpc. The nebular kinematic distance is about 1.8 kpc (Ardeberg & Maurice 1980), which we adopt in the following as the distance to the globules. The main globule is located at $\alpha_{\rm J2000.0}$: $11^{\rm h}38^{\rm m}16\overset{\rm s}{.}3$; $\delta_{\rm J2000.0}$: $-63°21'01''$.

Thackeray's globules have been studied with ground-based CCD images and millimeter observations by Reipurth et al. (1997, hereafter Paper I). Because the globules are located almost precisely along the line of sight to the OB stars, they appear as silhouettes against the bright H II region, thus allowing amazingly small features to be studied in fine detail. In Paper I we showed that the globule

[4] Based on observations made with the NASA/ESA *Hubble Space Telescope* at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

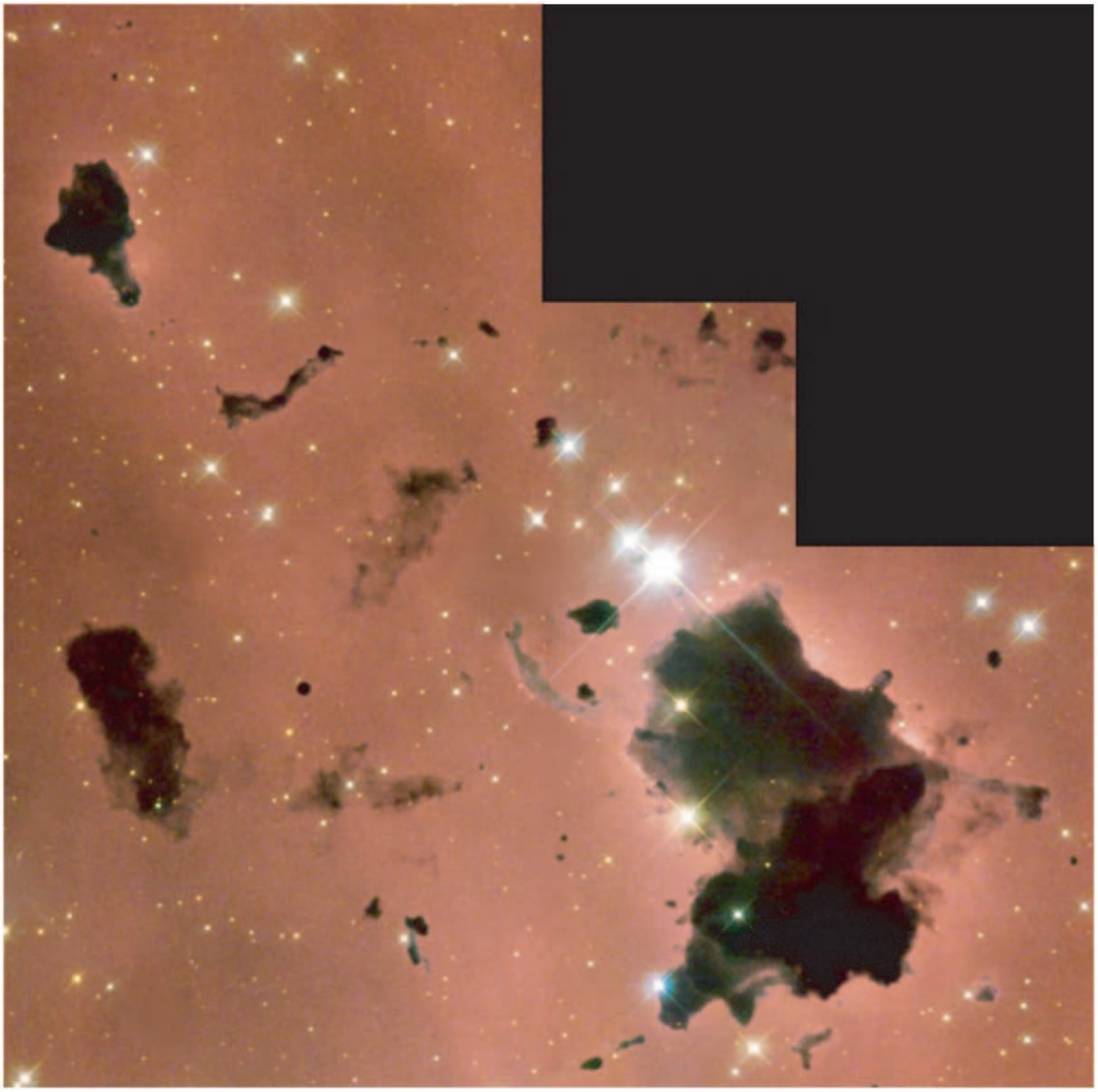

FIG. 1.—Thackeray's globules as seen with *HST*/WFPC2 an Hα filter combined with brief *B*, *V*, *R*, exposures. The width of the image is 160″.

complex contains a multitude of smaller splinters, which appear to have fragmented from the larger globules. The CO measurements show that the largest globule consists of two kinematically separate entities, with masses of 11 and 4 $M_{\odot}$. The millimeter observations revealed very large velocity differences, spanning 20 km s^{-1}, thus suggesting that the system is in a very dynamical phase at the moment. Searches for Hα emission stars were negative, and no infrared sources embedded in the largest globule were found by Moneti (1991), suggesting that the globules are not the site of widespread star formation. In Paper I we suggested that the globules could be the remnants of an elephant trunk that is breaking apart and which is observed from behind.

3.2. *Morphology of the Globules*

In Paper I we noted that, on ground-based images, the Thackeray globule complex contains a number of tiny fragments at the limit of resolution. In order to study these small splinters and to explore how small they can be, we have obtained *HST* WFPC2 images of the region around the main globule, Thackeray 1. In Figure 1 we show the entire field of the WFPC2 image, representing the easternmost region of the globule complex. The length and height of the image is 1.4 pc × 1.4 pc at the distance of 1.8 kpc. In Figures 2 to 4 we show the individual WF camera images and extend the numbering system for the globules used in Paper I for easier discussion of individual features.

When compared with the previous ground-based images, there are two things in the *HST* image that stand out. First, it is evident that there are two classes of globules, one with high extinction and very sharp edges, and another with much more fuzzy edges and a diffuse appearance. Second, there is no evidence for a large population of tiny globule splinters near the resolution limit of the image, as we speculated in Paper I.

Examples of the sharp-edged globules are numbers 16, 39, 31, 33, and 37, among others. Diffuse globules include numbers 12, 34. Finally, there are two objects that belong in both groups, Thackeray 1 and 3, which appear to represent transition objects between the two groups.

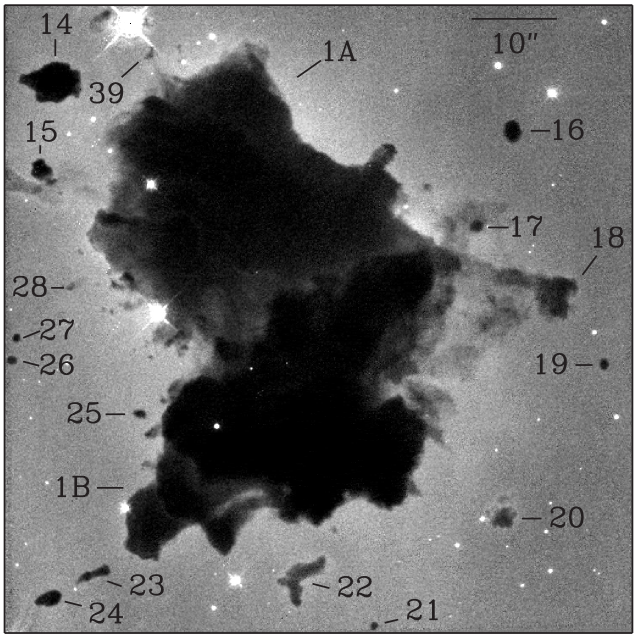

FIG. 2.—Principal globule, Thackeray 1, seen in the field of WF4. Various features are identified and labeled.

In the following two sections we discuss first the processes that are sculpting the largest globule, Thackeray 1, and then the nature of the ensemble of smaller globules.

4. THE LARGE GLOBULE THACKERAY 1

4.1. *Observed Properties*

This is the largest globule of the system, roughly covering a 30″ × 60″ area. The body of this globule has a complex structure, which is shown in more detail in Figure 5.

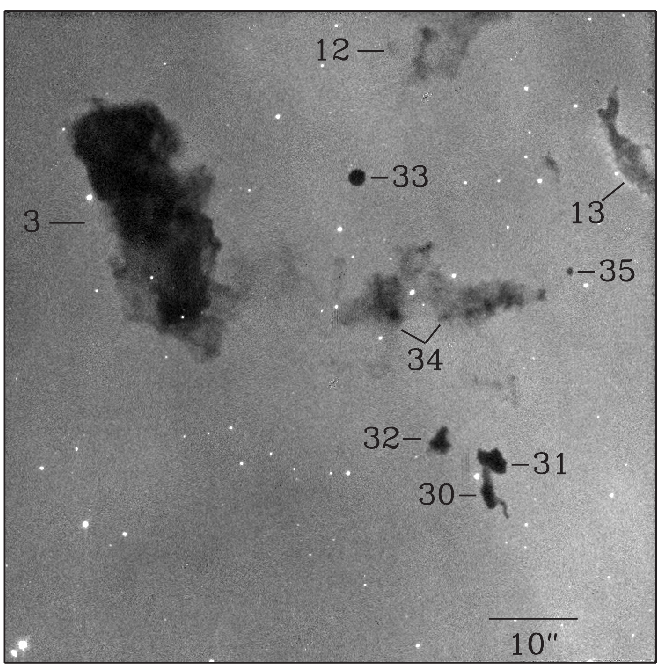

FIG. 3.—Thackeray 3 and surroundings, seen in the field of WF3. Various features are identified and labeled.

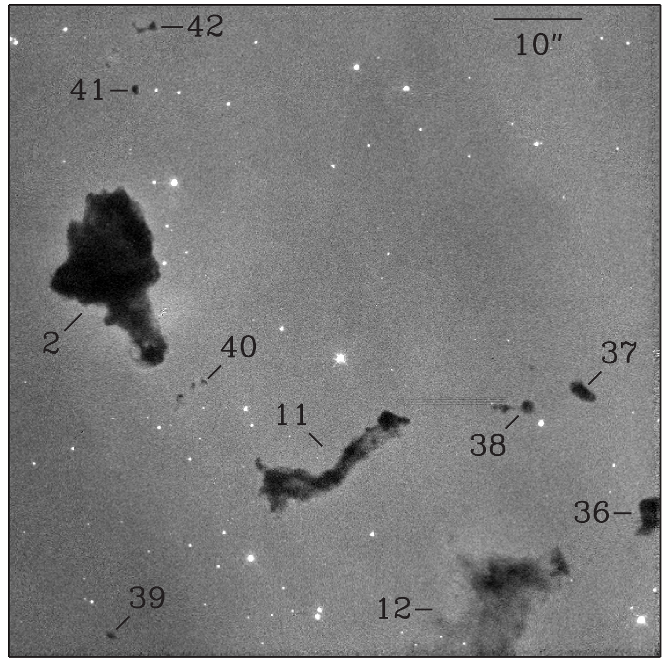

FIG. 4.—Thackeray 2 and surroundings, seen in the field of WF2. Various features are identified and labeled.

In this figure we have set the zero point of the intensity so that the H II region is at zero (and therefore any emission above the H II region is positive and regions with absorption are negative). Cuts across the globule show that there is enhanced Hα emission extending outward for $\sim 5'' \rightarrow 20''$ from the dark edge of the globule. This emission probably corresponds to the photoevaporated wind driven off the neutral cloud by the ionizing radiation field impinging on the side of Thackeray 1.

The edge itself varies substantially in sharpness. At some positions there is a sharp transition into the region of strong absorption over $\sim 1''$, while at other positions along the edge of the cloud there is a softer transition over $\sim 10''$ or more. The most extended transition region can be seen in the upper part of the image of Figure 5, where there is a "peninsula" that sticks out from the cloud into the H II region, extending over $\sim 20''$ and ending in Thackeray 18. This feature is discussed in more detail in the following section.

Thackeray 1 is clearly split into two structures, as was already clear from the CO data in Paper I, where we found the two parts to have a velocity difference of 5 km s^{-1}, with the northeastern part, Thackeray 1A, having $v_{\rm lsr} = -20$ km s^{-1} and the southwestern, Thackeray 1B, having $v_{\rm lsr} = -25$ km s^{-1}. A bright rim that crosses the globule defines the boundary between the two components. The western edge of Thackeray 1 is drawn out in a long tongue ending in globule 18. Such structure appears reminiscent of the curtains of gas and dust that are flowing away from the elephant trunks in M16 (Hester et al. 1996). As can be seen in the cuts through the cloud in Figure 5, the intensity rises gradually from left to right and then decreases sharply at the position of the boundary between 1A and 1B. Interestingly, in the cuts through the cloud we also see partial evidence of the existence of a second "edge," which could indicate that further subdivisions of Thackeray 1 might exist.

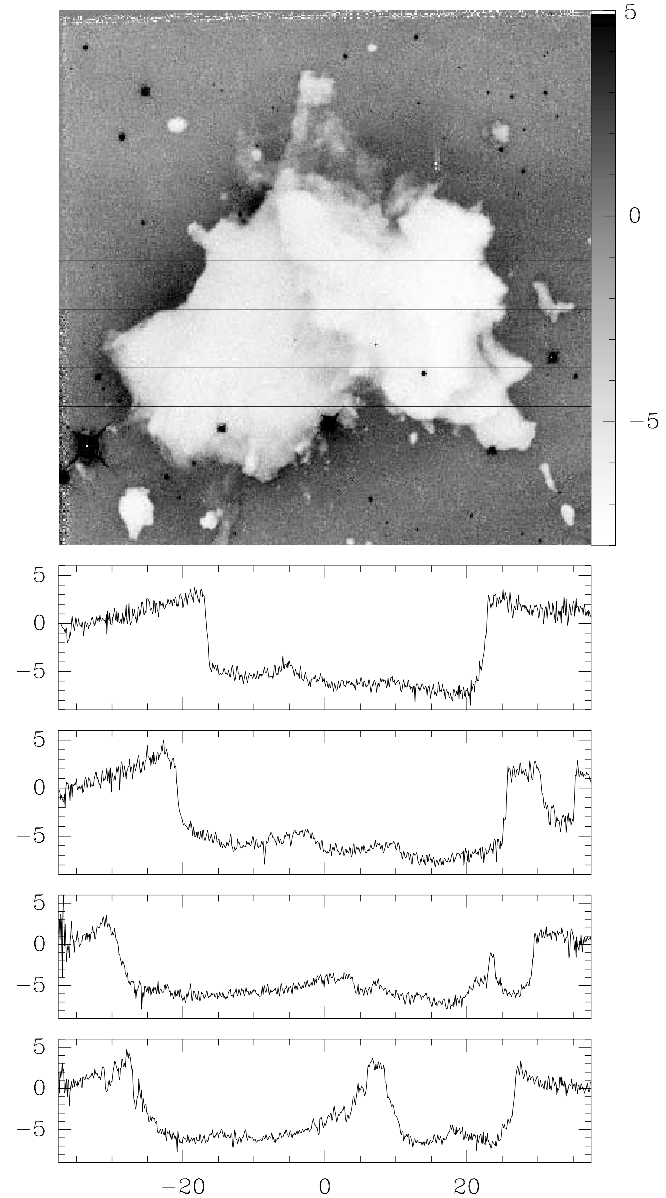

FIG. 5.—Largest globule with intensity cuts across four lines. It is clearly seen that there are two distinct globules, one (1B) partly covering the other (1A); see Fig. 2 for identifications.

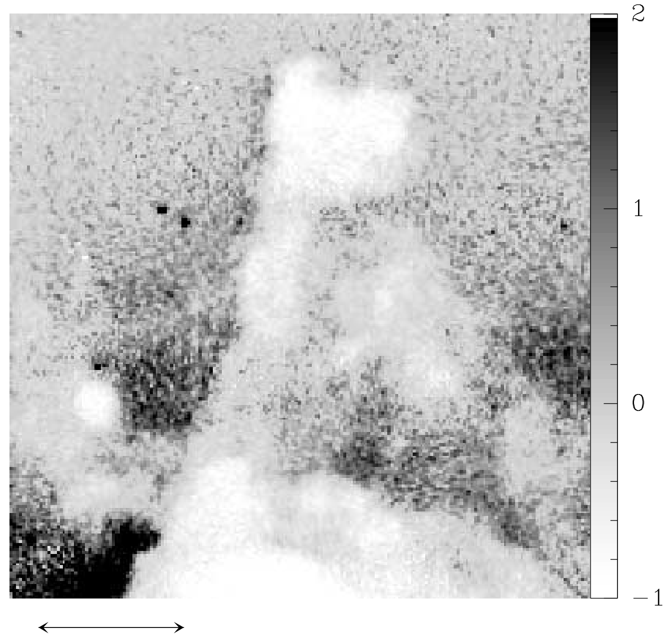

FIG. 6.—Optical depth of the partly diffuse feature including Thackeray 18 west of the main globule.

4.2. *Interpretation*

Let us first discuss the diffuse " peninsula " that ends in Thackeray 18 at the top of the image of Thackeray 1 shown in Figure 5. This region appears to be optically thin. One sees a complex structure in which the background H II region is partially visible. We have therefore used the contrast between the background H II region and the observed emission in order to compute the extinction optical depth. In Figure 6 we plot the spatial dependence of $\gamma = \ln (I/I_{\rm H\,II})$, where I is the spatially dependent intensity, and $I_{\rm H\,II}$ is the intensity of the background H II region (which we assume to be uniform). With γ defined in this way, negative values of γ correspond to regions with emission lower than the H II region, and positive γ-values correspond to regions with stronger emission.

There are relatively large regions, which have values of γ between -0.1 and -1 (implying extinction optical depths $\tau_d = -\gamma \sim 0.1 \rightarrow 1$). One can use this result to obtain an estimate of the number density through the empirical relation $\tau_d \approx 10^{-21} N_{\rm H}$, where τ_d is the optical depth (due to dust) and $N_{\rm H}$ is the hydrogen column density. We obtain that the hydrogen number density is

$$n_{\rm H} = \frac{N_{\rm H}}{L} = \left(\frac{10^{17}\ {\rm cm}}{L}\right)(10^3 \rightarrow 10^4\ {\rm cm}^{-3}) \qquad (1)$$

for $\tau_d = 0.1 \rightarrow 1$, where L is the size of the region (along the line of sight).

One can then estimate the time that such regions would last in the presence of the impinging photoionizing field:

$$t_{\rm ion} = \left(\frac{L}{10^{17}\ {\rm cm}}\right)\left(\frac{10^{49}\ {\rm s}^{-1}}{S_*}\right)\left(\frac{R}{1\ {\rm pc}}\right)\left(\frac{n_{\rm H}}{10^3\ {\rm cm}^{-3}}\right) 38\ {\rm yr}\ , \qquad (2)$$

where S_* is the ionizing photon rate of the exciting star and R is its distance from Thackeray 1. Therefore, for reasonable ranges of the input parameters we would conclude that these regions are essentially disappearing right as we are looking at them! The fact that we are seeing quite extended, diffuse regions with optical depths less than 1 is then rather strange, as they should not be present any more on timescales of a few decades.

A way around this apparent problem is that these regions could be in the shadows of the dense clumps, so that the impinging ionizing photon field would only correspond to the diffuse field from the nebula. This diffuse field could be very low if the nebula is not ionization bounded in the direction toward us, and therefore the lifetime of the optically thin regions could be larger than the value given by equation (2) by a factor of $\sim$10–100, giving $4000 > t_{\rm ion} > 400$ yr. Such a lifetime might be more consistent with the fact that at the present time we see extended, low-extinction regions.

This argument could be extended to try to explain the different properties found for the " edges " of the clouds. The " fluffy edges " could correspond to regions of Thackeray 1 that are in the shadow of other, optically thick regions. The sharp edges would then correspond to regions that curve away from the line of sight and become exposed to the direct radiative field from the ionizing source.

5. THE ENSEMBLE OF GLOBULES

5.1. *Observational Results*

In order to try to derive general properties of the system of globules, we have used a simple " structure detection " algorithm. This algorithm scans through the *HST* image, and labels all of the " dark clouds " present in the observed region. Each separate " cloud " is defined as a region of contiguous pixels, all of which independently satisfy a criterion for being " dark ", of the form $I \leq \eta I_{\rm H\,II}$ (where I is the intensity in the pixel, $I_{\rm H\,II}$ the intensity of the background H II region and $\eta < 1$ is a constant).

One can then find systems of " clouds " corresponding to different values of the constant η, which is used to define the pixels that are considered as being part of the clouds. Interestingly, we find that for $0.1 < \eta < 0.9$ our algorithm recovers very similar ensembles of clouds (a result of the fact that most of the clouds present in our image are actually very dark). We have then chosen $\eta = 0.5$, and only present the results obtained for this value of η. Comparing the detected clouds with the *HST* images, we see that all of the features seen in Figure 1 except the most diffuse clouds are indeed detected by our algorithm. We also find that a population of tiny objects with sizes of only a few pixels are picked up by the algorithm. Closer inspection shows that these are likely to be noise in the background, and we therefore cut off the object detection at $0\farcs5$, to be sure to exclude such artifacts.

We present the size distribution of the detected structures as a histogram which gives the frequency as a function of the square root of the area of the structures (representing an " effective radius "), the surface area being computed by adding up the number of consecutive pixels which define each structure. The resulting size distribution is shown in Figure 7.

From this figure, it appears that the " clouds " have a distribution with two components, one at a size of less than $1''$ and the second one at $\sim 1\farcs5$–$2''$. Also, there are a few clouds with characteristic sizes greater than $10''$, which form an extended wing to the size distribution.

Some examples of the structures corresponding to the smallest components of the size distribution are shown in Figure 8. It is clear that while a few of the structures appear to have roughly spherical morphologies, others are more irregular. The six structures which are more closely spherical have characteristic sizes $d_c = ({\rm area})^{1/2} = 0\farcs55$, $0\farcs62$, $0\farcs66$, $0\farcs79$, $0\farcs83$, and $1\farcs44$ (four of these being shown in Fig. 8). Therefore, all of these except one fall within the subarcsecond component of the size distribution function (see Fig. 7).

5.2. *Interpretation*

From our observations, we recover the size distribution of Thackeray's globules. The size distribution has a few clouds of characteristic sizes greater than $10''$ (corresponding to $\sim 3 \times 10^{17}$ cm at a 1.8 kpc distance). These large

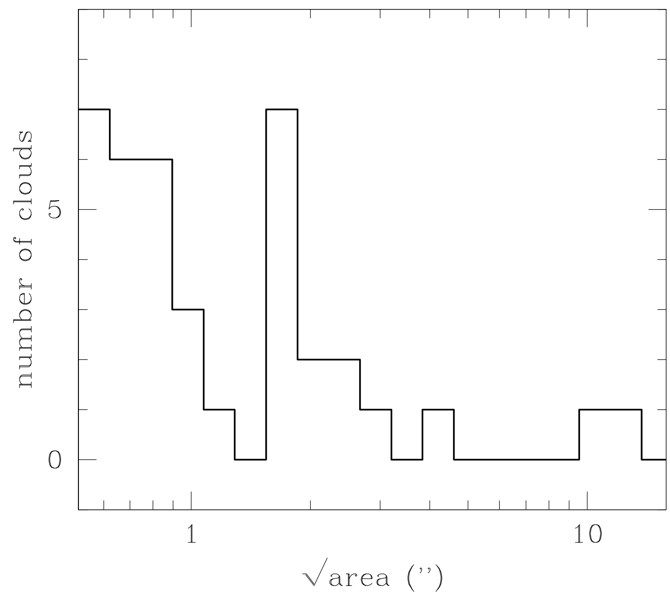

FIG. 7.—Histogram of globule sizes in the Thackeray globule complex.

clouds have visible internal structures, which either reflect their initial configuration (i.e., before they started interacting with the H II region) or alternatively could be the result of the H II region/cloud interaction. Given the fact that these clouds show unusually large CO velocity dispersions (see Paper I), the second of these possibilities appears to be more likely.

Associated with the edges of these clouds we find a number of small fragments, which apparently have been left behind in the process of photoevaporation and/or ablation of the clouds. Unfortunately, the theory of these processes is very complex and still not developed to the point where a meaningful interpretation of these observational results could be carried out.

Reviews on the theory of formation of structure in expanding H II regions are given by Williams, Dyson, & Pavlakis (2000) and Williams et al. (2003). Kahn (1958) suggested that instabilities in D-type fronts would be damped by the diffuse Lyman continuum, a result that is partially confirmed by the linear stability analysis of Sysoev (1997). However, in many situations the dense ionization front/shock wave layer formed in D-type fronts is indeed highly unstable, as a result of thin shell (Giuliani 1979; Vishniac 1983; Sysoev 1998) or Rayleigh-Taylor instabilities (present when the ambient density decreases away from the source, Capriotti 1973; Franco, Tenorio-Tagle, & Bodenheimer 1990). " Shadowing instabilities " (Williams 1999) can also occur. These instabilities arise as small inhomogeneities present within the region of rapid (R-type) ionization front expansion affect the later transition to a D-type front, producing a surprisingly strong corrugation of the dense, shocked layer.

It is still an open question whether any of these instabilities spontaneously generates structures such as the " elephant trunks " observed in H II regions (e.g., Frieman 1954; Hester et al. 1996). From the fact that these structures appear to be strongly localized, one would suspect that actually the nature of the " seed " perturbation is important for producing them.

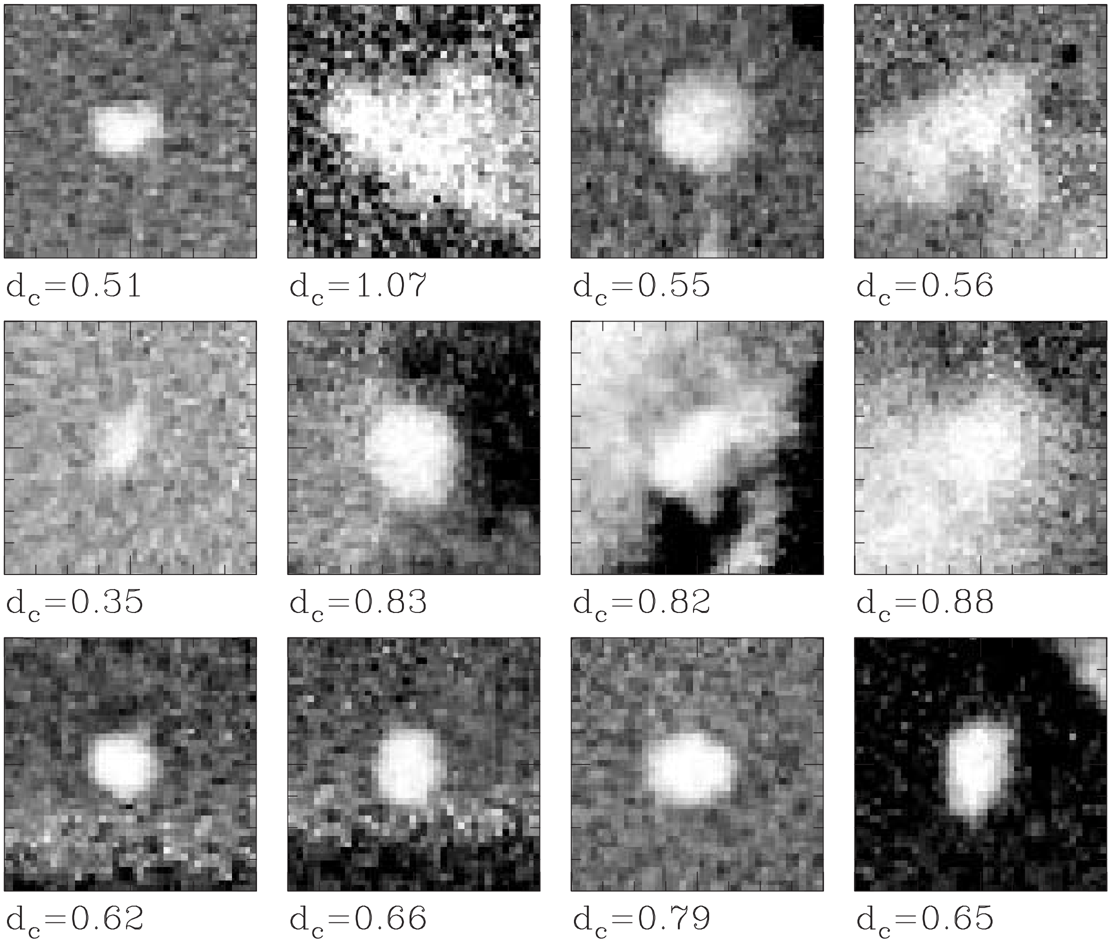

Fig. 8.—Sample of the smallest globule splinters in the Thackeray globule complex. Each panel is $4'' \times 4''$, corresponding to a width of 7200 AU.

Following this idea, a number of studies have been made of the interaction of ionization fronts with dense "clumps" (Bertoldi & McKee 1990; Lefloch & Lazareff 1994; Mellema et al. 1998) and the flows produced in their shadows (Cantó et al. 1998; Pavlakis et al. 2001). These studies show that preexisting stationary atomic or molecular structures can be strongly compressed and stirred up by trapped, D-type ionization fronts. However, these studies are limited to the case of initially spherical, dense clumps (more complex geometries having only been explored with simulations, which do not include the important effects of the ionization front itself; see, e.g., Poludnenko, Frank, & Blackman 2002) and probably cannot be applied in a direct way to the much more complex case of a real H II region expanding into an inhomogeneous medium.

An effort toward studying the propagation of ionization fronts into more complex structures has recently been carried out by Lim & Mellema (2003). These authors place two dense, spherical structures (with different relative positions) in the way of a travelling ionization front and show that very complex structures are produced as a result of its interaction with the clouds. Models such as these could be used to obtain predictions of the size distribution of the cloud fragments produced in the H II region/cloud structure interaction, and such predictions could be used to try to interpret the observed size distribution (see Fig. 7).

Such a comparison between models and observations might elucidate whether the two peaks (at $d_c < 1''$ and $1''.5$; see Fig. 7) in the cloud size distribution have to be present in the initial structure of the neutral gas or whether these characteristic sizes can be created in the H II region/cloud interaction process.

Of particular interest is the fact that several almost perfectly spherical globules are present. Seeing the very complex flows obtained from the simulations of Williams (2003) and Lim & Mellema (2003), it is somewhat surprising that such apparently simple structures are indeed observed within the system of Thackeray's globules.

An example of one of these spherical clouds is shown in Figure 9. A cut through the center of the cloud shows that its edges are very sharp (the transition from H II region to dark cloud occurring over $\sim 0''.2$), and that the cloud itself has no visible internal structure. Also, there is no indication of the presence of emission from a photoevaporated flow, which would produce a bright "halo" around the edge of the clump. Such haloes are clearly seen in some of the irregular clouds of the system, but they are apparently absent (at least to within the signal to noise of our observations) in the more spherical clumps. This may be because the spherical clouds are rather small and the line of sight through their photoevaporation flows is too short to be detectable.

The fact that some of the clumps are spherical suggests that they might be self-gravitating. In order to estimate their

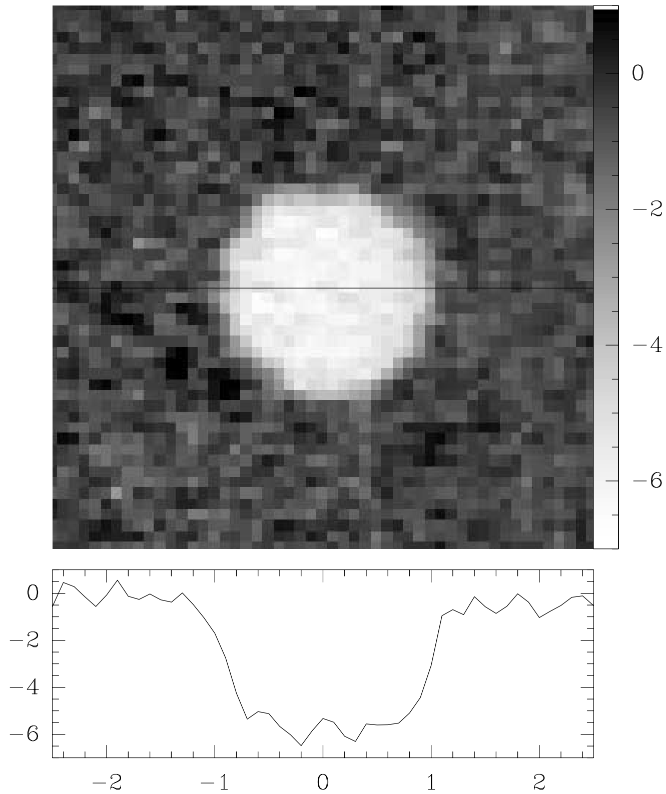

Fig. 9.—Example of a small near spherical globule. The intensity cut shows that the globule has remarkably sharp edges.

mass we can then take the self-gravitating, singular, isothermal sphere solution to compute a mass $M_c \approx 0.01\ M_\odot\ (T/10\ \mathrm{K})(d_c/0\farcs8)$ (where T is the clump temperature and d_c is its characteristic size).

This mass estimate should be regarded as an upper limit to the mass of the clouds, as the clouds could have flatter density structures than the singular solution and therefore have lower masses for their sizes. We would therefore conclude that, if the more spherical clumps in our sample are indeed self-gravitating, they should then have masses of a few times the mass of Jupiter.

6. EVAPORATION VERSUS FRAGMENTATION

The histogram of numbers of globules versus their size in Figure 7 may hold clues to the origin of the small globules. If we have a distribution in a N versus d diagram that is initially flat and we for simplicity assume that the globules are homogeneous and of equal density, then the distribution will soon start to be depleted among the smallest globules. This is because the evaporation is proportional to the surface area, i.e., to r^2, whereas the mass is proportional to the volume, i.e., to r^3. Such an initial distribution could never reproduce the observed histogram in Figure 7. We would have to have an initial distribution that was heavily weighted toward smaller globules, and even then we would have to observe the globule system in a not too evolved state, before all the small globules were gone.

One way we could conceivably reproduce the observed size distribution of the globules would be if we assume that there is one more process that contributes to the destruction of the globules, namely, fragmentation. The largest globule, Thackeray 1, shows three possible mechanisms that could lead to the production of smaller globules. First, on its eastern side, Thackeray 1 shows a number of outcroppings and small globule splinters, including numbers 25 and 28. The proximity of the clumps number 26 and 27 to the large globule suggests that they also once broke off from the bigger globule. Second, on its western side, Thackeray 1 has the fuzzy tail that ends in globule number 18. If this is material that is ablated from the side of the large globule, then, apparently, clumps can also be torn off in the ablation process. Finally, the location of globules 23 and 24 as an extension to the pointed southeast corner of Thackeray 1B could point to a hydrodynamical instability that nips off fragments from long filamentary structures.

Whatever the fragmentation mechanism, if small globules are continuously produced, then the competition between their formation through fragmentation and their destruction through evaporation will shape the size distribution of the globule system and may lead to the observed distribution.

Finally, we note that because of the size dependency on the lifetime of globules, fragmentation will considerably speed up the destruction of a large globule. Regions like Thackeray's globules may therefore be rather short-lived phenomena.

7. CONCLUSIONS

We have acquired Hα-band images of Thackeray's globules using WFPC2 on board *HST*, in a follow-up to our previous ground-based study of this globule complex (Reipurth et al. 1997), and have obtained the following results:

1. Examination of the *HST* images shows that there appear to be two distinct types of globules: compact, exceptionally sharp-edged ones, on the one hand, and fuzzy and diffuse globules, on the other hand. Two globules show some of both characteristics, suggesting that one category may transform into the other.
2. Calculations of the lifetime of the globules suggest that all but the largest should evaporate very quickly. The presence of large numbers of globules in all sizes suggests that either we are seeing the globule system at a very special moment in time or some of the globules have been protected for some time by the shadows of larger globules.
3. The presence of very small globules, with correspondingly very short lifetimes, suggests that there is a continuous production of such splinters. We review the current views on the formation of structure in neutral inclusions in H II regions and conclude that there is no unique link between observations and theory at this stage.
4. The size distribution of globules could result from fragmentation processes in the larger globules. We find several indications that the globule complex is shaped by fragmentation and note that, because smaller globules evaporate faster by a factor of $1/r$, fragmentation may greatly increase the rate of destruction of the globules.

B. R. acknowledges support from STScI grant HST-GO-07381.01-A and NASA grant NAG W-3192 (LTSA).

REFERENCES

Ardeberg, A., & Maurice, E. 1980, A&AS, 39, 325
Bertoldi, F. 1989, ApJ, 346, 735
Bertoldi, F., & McKee, C. F. 1990, ApJ, 354, 529
Bok, B. J., & Reilly, E. F. 1947, ApJ, 105, 255
Cantó, J., Raga, A. C., Steffen, W., & Shapiro, P. 1998, ApJ, 502, 695
Capriotti, E. R. 1973, ApJ, 179, 495
Dyson, J. E. 1973, A&A, 27, 459
Franco, J., Tenorio-Tagle, G., & Bodenheimer, P. 1990, ApJ, 349, 126
Frieman, E. A. 1954, ApJ, 120, 18
Giuliani, J. L., Jr. 1979, ApJ, 233, 280
Herbig, G. H. 1974, PASP, 86, 604
Hester, J. J., et al. 1996, AJ, 111, 2349
Kahn, F. D. 1958, Rev. Mod. Phys., 30, 1058
———. 1969, Physica, 41, 172
Lefloch, B., & Lazareff, B. 1994, A&A, 289, 559
Lim, A., & Mellema, G. 2003, A&A, 405, 189
Mellema, G., Raga, A. C., Cantó, J., Lundqvist, P., Balick, B., Steffen, W., & Noriega-Crespo, A. 1998, A&A, 331, 335
Moneti, A. 1991, in ASP Conf. Ser. 14, Astrophysics with Infrared Arrays, ed. R. Elston (San Francisco: ASP), 261
Oort, J. H., & Spitzer, L. 1955, ApJ, 121, 6
Pavlakis, K. G., Williams, R. J. R., Dyson, J. E., Falle, S. A. E. G., & Hartquist, T. W. 2001, A&A, 369, 263
Poludnenko, A. Y., Frank, A., & Blackman, E. G. 2002, ApJ, 576, 832
Reipurth, B. 1983, A&A, 117, 183
Reipurth, B., Corporon, P., Olberg, M., & Tenorio-Tagle, G. 1997, A&A, 327, 1185 (Paper I)
Sysoev, N. E. 1997, Astron. Lett., 23, 409
———. 1998, Astron. Lett., 24, 535
Tenorio-Tagle, G. 1977, A&A, 54, 517
Thackeray, A. D. 1950, MNRAS, 110, 524
Thackeray, A. D., Wesselink, A. J. 1965, MNRAS, 131, 121
Vishniac, E. T. 1983, ApJ, 274, 152
Walborn, N. R. 1973, AJ, 78, 1067
———. 1987, AJ, 93, 868
Williams, R. J. R. 1999, MNRAS, 310, 789
———. 2003, Rev. Mexicana Astron. Astrofis. Ser. Conf., 15, 184
Williams, R. J. R., Dyson, K. E., & Pavlakis, K. 2000, Ap&SS, 272, 155