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THE AGES OF THE STARS THAT ILLUMINATE THE COMETARY NEBULAE

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When one looks at pictures of the nebulous regions of the Milky Way, one is struck by the remarkable abundance of conical or parabolic nebulae (loosely called "elephant trunks", bright rims, etc.) These occur both as dark clouds or as bright (reflexion or emission) nebulae*. By considering a single complex of clouds one can easily see that their actual sizes vary considerably, and that frequently there are rows of cones resembling wave trains. There is no question about the reality of these structures, but the nature of the process which gives rise to them is not so clear. Since it is not the purpose of this note to discuss the physics of the conical nebulae, we shall only mention briefly the more plausible explanations.

a) The conical nebulae are the result of an instability in the interface between two fluids of different density when there is a field of acceleration directed from the light fluid towards the dense one (for instance at the boundary of a young H II region expanding into the surrounding neutral gas). This Rayleigh-Taylor instability has been applied to the case of interstellar clouds by Frieman⁽¹⁾ and Layzer⁽²⁾.

b) Pottasch⁽³⁾, on the other hand, has opposed the above interpretation on the grounds that the more pointed configurations should be the younger ones, according to the prediction of the R — T instability, while they are found closer to the exciting star (center of the H II region), which is interpreted as a sign of advanced age. Also, as Khan⁽⁴⁾ has shown, when the boundary of the cone is considered an ionization front which advances into the dark material, the boundary is stable in most of the cases of astrophysical interest. Pottasch and Khan think, therefore, that the cones are the result of the compression and deformation of, previously existing, dense inclusions in the H II regions, as the result of the expansion of the latter. The fact that the cones frequently appear in wave trains (for instance in I C 405) as well as in dark regions, seem to indicate that we cannot yet completely rule out the importance of the R — T instability.

In any of the above interpretations the conical nebulae are regions of high density, in fact some of them are the densest nebulae on record. For instance, Pottasch⁽⁵⁾ has found that the mean density of dark matter in the most pointed configurations (class 4 in Pottasch's classification) is 1.3×10^6 atoms/cm^3; Pottasch has also calculated that for their radii of curvature, these nebulae begin to be gravitationally unstable at densities larger than 1.7×10^5 atom/cm^3, which means that conical nebulae of class 4 are in contraction. Obviously this result strongly suggest that, of all known nebulae, the most favourable ones for the formation of stars are the most pointed dark conical nebulae.

Dibai⁽⁶⁾ has pointed out the convincing similarities between the conical and the classical cometary nebulae showing that, since the vertices are the more compressed regions, it is there where —in general— the first stars should be born; hence there are good reasons to consider the cometary nebulae as an advanced stage of development of some of the pointed dark conical nebulae.**

In the preceeding paper⁽⁸⁾ we gave reasons to expect that very young stars of intermediate masses should be surrounded by a circumstellar cloud which flattens with time, hence an observer outside of the conical nebula may contemplate the following sequences of structures:

1) A cometary nebula without a visible exciting star. This case corresponds to a very young star whose opaque disk of planetesimals is in the same plane as the observer, but such that the axis of the nebula is out of the principal plane. The star, beeing in its early Hayashi phase of high luminosity, may easily illuminate its conical nebula, although for an outside observer it will be hidden and invisible. Example of this case are probably the nebula B 14 and the cometary nebulae Nos. 5a and 6a found by Haro⁽⁷⁾ in Orion.

2) The following step in time will be when the growth of the planetesimals lets some visible light out in the principal plane; again, if we are in the principal plane, we will see a cometary nebula but now with a faint star in the vertex; the color of the star may be redder than that of the nebula as we may except to have some residual extinction in the principal plane, which is not seen from the nebula (when it is out of the principal plane). An example of this case could be the cometary nebula B 10 and Haro's 13a.

3) A more advanced stage combined with a different geometry will produce the more classical

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* A good example is the conical nebula in NGC 2264 pointing to H D 47 887.

** Because of entirely different reasons, Haro first proposed⁽⁷⁾ that the stars at the vertices of cometary nebulae were condensed out of the cometary material and that, consequently, these nebulae existed quite independently of the stars at their vertices.

cometary nebulae which are variable when their axis are close to the principal plane. If we observe them from a direction away from the principal plane, the illuminating star would appear brighter than in the preceeding two cases. The prototypes of this stage are Hubble's and Hind's variable nebulae, as well as the nebula connected with R Corona Australis. As explained in the preceeding paper, the variability of the nebulae is due to a complex sequence of eclipses produced by the clouds of planetesimals when are about to become planets, without excluding the contribution of the intrinsic variations in the luminosity of the illuminating star.*

Thus starting from Pottasch results on the high density of some conical nebulae we are led naturally to the conclusion that cometary nebulae are very young (and transitory) configurations illuminated by even younger stars; hence we may ask now; Is this conclusion supported by what we know about the stars at the vertices of cometary nebulae? And if so, can we set an upper limit to the ages of these stars?

Of course, the answer to the first question is in the affirmative, since R Monocerotis, T Tauri** and R Corona Australis are well known T Tauri stars whose youth is well established. In fact, Ambartzumian(9) has pointed out that one of the most characteristic features of these nebulae is their involvement with T Tauri stars.

To estimate the ages of the stars that illuminate the cometary nebulae, we have to consider that the star in the vertex is only a small fraction of the total mass in the cometary nebulae ($\approx 1/500$), and that once the star is formed it keeps the motion of the local eddy from which it condensed. Since it is well known that the random motions inside dark clouds are of the order of 2 km/sec.(10) (which, by the way, is comparable to the random motions of young stars in clusters) it is quite easy to calculate how long it will take for the recently formed star to drift out of the vertex of the "comet". For a number of representative cometary nebulae taken from the paper by Dibai(6), we have estimated the "characteristic radius" Rc of the vertex, out of which the star will not look any more involved in the nebulosity. Our estimates were based in rough measurements over the best photographs that we could find in the literature. The definition of this radius is somewhat arbitrary, however an examination of the photograph of Hubble's nebula by Hall(11) may convince the reader that in some cases it is not a difficult matter to estimate Rc. In Table I we list the pertinent data for a number of cometary nebulae which seemed more representative of their class; in columns 2 — 9 we give, in the usual order, the name of the nebulae, the stars involved in their vertex, their cordinates, their distance in parsecs, their Rc in seconds of arc, their Rc in astronomical units, and the time T in years necessary for the stars to move the distance Rc with the mean velocity of 2 km/sec. At the bottom of the Table we give the sources where Rc was measured and the references to the distances. The times listed, which are upper limits to the ages of the stars, range from 6 000 years to 52 000. The mean age of the group is therefore 19 000 years.

We may conclude therefore that dark conical nebulae are the birth places of stars, (we do not imply they are the only places!), that the first stars to be formed are at their vertices, and that given the appropiate perspective and stage of development we see them as variable cometary nebulae. Finally, the mean age of a representative sample of these objects is found to be $\approx$ 19 000 years, which places them in the same age bracket (10 000 to 20 000) as the Trapezium stars(13) and the emission nebula in Orion.(14) (15)

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* If the star has a large convective region and is rotating fast, we should expected the existence of glorified "sunspots" which will produce nonisotropic and irregular variations in light.

** The cometary appearance of Hind's nebula is somewhat washed out; however, in a photograph of 1914 reproduced by Herbig(12) one can see a faint bridge of luminosity in between, making the whole structure resemble a comet. A similar situation is encountred in B 10 with respect to star "b" of Kholopov. See reference (a).

TABLE I

	Nebula	*Star*	α *1900*	δ *1900*	*D* *(parsecs)*	R_c''	R_r *(A. U.)*	*T (years)*
1	B 10	Star "b" Kholopov	$4^h\,12^m21^s$	+28°02′	150	40 (a)	6×10^3	15×10^3
2	96 B	R Y Tau	4 15 45	28 12	150 (b)	20 (b)	3×10^3	7.5×10^3
3	Hind	T Tau	4 16	19 18	150	20 (c)	3×10^3	7.5×10^3
4	100 B	D G Tau	4 20 58	25 53	150	60 (d)	9×10^3	22.5×10^3
5	122 B	HI HK	5 25 50	12 05	400	15 (d)	6×10^3	15×10^3
6	Haro 13a	———	5 33 55	− 7 10	400	20 (d)	8×10^3	20×10^3
7	Anon in 35B	FU Orionis	5 39 54	+ 9 02	400	20 (d)	8×10^3	20×10^3
8	Hubble	R Mon	6 33 42	8 50	700 (f)	10 (e)	7×10^3	17.5×10^3
9	S 167	Lk Hα 59, 61, 62, 63	6 36	9 32	700 (f)	30 (f)	21×10^3	52.5×10^3
10	NGC 6729	R Cr A	18 55 09	−37 06	150 (i)	15 (g)	2.25×10^3	5.6×10^3
11	Anon in I .C 5070	Lk Hα 155	20 48 0	+43 52	500 (h)	20 (d, h)	10×10^3	25×10^3

(a) Struve, O. Sky and Telescope **22**, 197; 1961.
(b) Herbig, G. Ap. J. **133**, 337; 1961.
(c) Herbig, G. Astr. Soc. Pacific, Leaflet No. **293**, 1953.
(d) Palomar Sky Atlas.
(e) Hall. R. C. Ap. J. **139**, 759; 1964.
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(g) Whitney, W. T. and Weston, F. B. Ap. J. **107**, 371; 1948.
(h) Herbig, G. Ap. J. **128**, 259; 1958.
(i) Aller, L. H. *Gaseous Nebulae* p. 103 (Chapman & Hall, 1956).

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