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DUST IN AND NEAR THE ORION NEBULA

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RESUMEN

El modelo más aceptado de la Nebulosa de Orión es el de una ampolla, pero el modelo alternativo donde la apariencia de la nebulosa está determinado por autoextinción jamás ha sido realmente desechado. Hago un resumen de ambos modelos y muestro que las evidencias están fuertemente en contra del modelo de autoextinción y favorecen al de ampolla.

ABSTRACT

Although the blister model for the Orion Nebula is widely accepted, an alternative model, where the optical appearance of the nebula is primarily determined by self-extinction, continues to be considered by some and has never specifically been disproven. I summarize the characteristics of the two models and show that the evidence falls overwhelmingly against the self-extinction model and in favor of the blister model.

Key Words: **DUST, EXTINCTION — H II REGIONS — ISM: INDIVIDUAL (ORION NEBULA)**

1. THE BLISTER MODEL FOR THE ORION NEBULA

The widely accepted physical model for the Orion nebula is that of a thin blister of photoionized gas on the side of the molecular cloud OMC-1 facing the observer. This model was introduced (Zuckerman 1973, Balick, Gammon, & Hjellming 1974) primarily to explain the differential velocities of various states of ionization (Kaler 1967), where the lowest ionization lines have velocities identical to the molecular cloud and the highest ionization lines are blueshifted about 10 km s^{-1}. This is the behavior one expects if θ^1 Ori C sits in front of the molecular cloud, photoionizing the neutral gas, which then expands away from the local ionization front and drops in density approximately exponentially. The scale height of the emissivity is only 0.025 pc and the star is about 0.25 pc in front of the nebula. The process of photoevaporation is driven by the ionizing flux from θ^1 Ori C, which means that the rate will be lower further from the star and this explains qualitatively why the density of the nebula systematically drops with increasing apparent distance from θ^1 Ori C. Adopting this basic model has allowed the derivation of a 3-dimensional map of the surface of the nebula (Wen & O'Dell 1995) and the detailed features of the model have recently been reviewed (O'Dell 2001).

This widely accepted model also includes a nearby foreground lid (or veil) of material at about three times the distance between θ^1 Ori C and the main ionization front. It is highly irregular in optical depth, but generally increases from the SW to the NE, with the most optically thick portions producing the striking Dark Bay feature that appears in optical wavelength images. Van der Werf & Goss (1989) have established that there is strong 21-cm absorption from H I, indicating that the foreground lid is neutral. The column density of H I correlates well with the reddening of the emission from the nebula (O'Dell, Walter, & Dufour 1992) and one sees absorption lines in the early spectral type stars' continua which arise from the lid (O'Dell et al. 1993).

2. AN ALTERNATIVE, OPTICALLY THICK MODEL FOR THE ORION NEBULA

A logically self consistent alternative model is that the appearance of the nebula is largely determined by the nebula having a significant optical depth in visual light, i.e., the nebula is optically thick. In this model the thin layer of visible material is seen because would one only see the surface layer of an optically thick ionized gas, a position advocated most eloquently by Guido Münch (1958; 1985) and Gómez Garrido & Münch (1984). If one employs only a slightly enhanced interstellar dust to gas ratio this would explain the thin layer of the nebula.

The most quantitative argument for high internal extinction within the nebula lies in the study of the Hα/Hβ/Hγ flux ratio as determined for many positions in the nebula with a photoelectric multichannel spectrometer (Münch & Persson 1971). As demonstrated most clearly by Leibowitz (1973) the effects of self-extinction will alter the slope in a

Balmer decrement color-color diagram (Figure 1). For the Whiteoak (1966) extinction curve for Orion, the slope in the color-color diagram should be 0.30 for extinction by foreground material and 0.24 for self-extinction. Münch & Persson (1971) found an average slope of 0.225±0.060 and accepted this as evidence for self-extinction. However, there was the disturbing feature that a projection of the observed points back to zero extinction did not pass through the theoretically predicted values of Pengelly (1964), making it appear that there was a systematic photometric error. It is impossible to fully assess the discrepancy. The method of observing employed continuum corrections determined only at two wavelengths, 4530 Å and 8060 Å and it is likely that variations of the color of the nebula significantly affected the continuum corrections, thus throwing off the derived Balmer decrements. However, even if one dismisses the Balmer decrement argument, one must evaluate the optically thick model since it does explain the thin layer apparent structure of the nebula.

There have been numerous models calculated to explain the variation in the scattered light continuum of the Orion Nebula, many of which assume that the scattering particles are close to the Trapezium stars and thereby resemble the optically thick model. However, scattered light distributions are not a strong determinant of the properties of the particles doing the scattering or their distribution (White, Schiffer, & Mathis 1980) because there are too many free parameters in the predictions.

3. DISCUSSION OF THE TWO MODELS

In this section, I wish to discuss the factors favoring the position that the thin blister of the Orion Nebula is not produced by high self-extinction. This will involve an assessment of the Balmer decrement spectrophotometry that supported the self-extinction model, comparison of extinctions derived by quite different methods, and structures within the nebula that argue against strong self-extinction.

3.1. *The Balmer Decrement Color-Color Diagram*

As mentioned in the previous section, one of the few quantitative arguments for strong self-extinction was the spectrophotometric study of the first three Balmer lines by Münch & Persson; however, their results indicated a discrepancy with theoretical predictions at low values of the extinction. Since that study did not include use of already published data and there have been numerous observations since, it is worth compiling the results of several other studies, which is done in Figure 1. In this figure one sees a high dispersion in the observed Balmer decrement, but the observations clearly favor a slope expected from primarily foreground extinction. In addition, the data easily extrapolate back at zero extinction to the theoretically expected ratios. There is a systematic photometric difference between these four spectrophotometric studies spanning over three decades and the Münch & Persson results in the sense that at $\log[F(\mathrm{H}\alpha)/F(\mathrm{H}\beta)] = 0.5$, their $\log[F(\mathrm{H}\beta)/F(\mathrm{H}\gamma)] \simeq 0.40$, in contrast with 0.34 in Figure 1. In the light of this established systematic error, it seems inappropriate to use small differences of slope to argue for strong self-extinction.

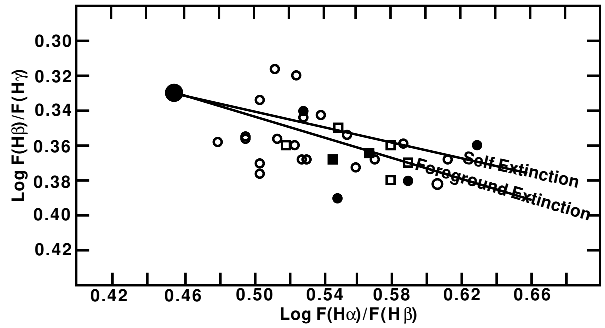

Fig. 1. Observed Balmer line ratios are shown here and compared with the theoretical value of Pengelly (1964, large filled circle). Open circles are from Baldwin et al. (1991), filled squares Esteban et al. (1998), filled circles O'Dell & Hubbard (1965), and open squares Simpson (1973). The upper curve represents the expected reddening if self-extinction was dominant and the lower the expectation if foreground extinction was dominant.

3.2. *A Recent Comparison of Radio and Optical Observations*

A recent investigation of the Orion Nebula with the VLA at 20 cm and with the *HST* in optical emission lines has allowed the derivation of the extinction across the nebula at 1.7″ spatial resolution (O'Dell & Yusef-Zadeh 2000). Since the ratio of the radio continuum to the Balmer lines is insensitive to the electron temperature and that temperature is adequately well known, the results should be quite accurate. We found that the extinction is highly variable, reaching a maximum in the Dark Bay. In a self-extinction model, the extinction should be quite uniform, except for any additional foreground extinction.

This study also derived extinction for a smaller region imaged in both Hα and Hβ, this being done from the $F(\mathrm{H}\alpha)/F(\mathrm{H}\beta)$ line ratio. The agreement with the 20 cm/Hα result was excellent, the ratio of 20 cm/Hα to Hα/Hβ extinction being 0.93±0.19. As

Leibowitz (1973) has shown, the extinction derived from the Hα/Hβ flux ratio (assuming that the nebula is optically thin whereas it is actually optically thick) would be about twice the extinction derived from comparing 20 cm and Hα observations.

The fact that the extinction of the Trapezium stars agrees with that derived from the 20 cm/Hα study also argues that the extinction occurs in the foreground. The derived extinction of the three brightest Trapezium stars is $A_V = 1.55$ (Johnson 1967), which scales to the logarithmic extinction coefficient $c_{\mathrm{H}\beta} = 0.71$ which is in excellent agreement with the 20 cm/Hα study results (cf. Figs. 2 and 3 of O'Dell & Yusef-Zadeh 2000). This agreement means that the extinction occurs in front of both the Trapezium stars and the nebula, which could not be the case for dominant self-extinction.

The 20 cm/Hα study also reveals large clouds that lie beyond the Dark Bay portion of the foreground extinction which are photoionized on the side facing θ^1 Ori C, a condition that could only exist if the star was between the layers producing the extinction and the bright emission.

3.3. *Additional Arguments against Dominant Self-Extinction*

We see numerous properties in the Orion Nebula which are natural results of the blister model but not the self-extinction model. Individually and collectively they strengthen the case.

High velocity resolution studies (e.g., Castañeda 1988) have revealed a redshifted "echo" of the primary emission line. This is explained (O'Dell et al. 1992, Henney 1998) as being light originating in the main emitting layer that is scattered in the high density neutral zone immediately beyond the ionization front. The redshift is the result of scattering by a layer that is moving (the process doubles the relative velocity) and the lines are broadened by emitting/absorbing processes occurring over a variety of relative velocities.

The well defined velocity and density (O'Dell 1994) gradient is a natural property of a photoionized blister, which is not expected from anything except a quite contrived self-extinction model.

We now know that there are numerous linear features in the Orion Nebula in addition to the Bright Bar running NE–SW and passing near θ^2 Ori A (O'Dell & Yusef-Zadeh 2000). Such features are difficult to explain with the self-extinction model, but are easily explained in the blister model as escarpments on the surface of the nebula where the ionization front is viewed almost along the line of sight.

Finally, O'Dell et al. (1992) showed that there is a good correlation of the column density of H I, as determined from the 21 cm absorption line, and the extinction derived from the $F(\mathrm{H}\alpha)/F(\mathrm{H}\beta)$ ratio. The H I forming the absorption line in the continuum radiation of the nebula can only be found in a neutral zone. If the self-extinction model was correct there should be no correlation. The derived correlation indicates that the amount of extinction is about that expected if the average interstellar medium (ISM) dust/gas ratio applies.

3.4. *A Caveat*

Although I have presented numerous pieces of evidence here for the blister model and against the self-extinction model, I cannot say that self-extinction plays zero role. If the average interstellar dust/gas ratio applied to the ionized nebular gas, then A_V would be about 0.65 along a line of sight looking straight into the nebula (O'Dell & Yusef-Zadeh 2000). However, general interstellar extinction is a combination of both scattering and absorption, and only the latter will be important in determining the apparent structure. Moreover, there are independent arguments that in the central region the dust/gas ratio must be less than the average for the ISM. Ferland (2001) argues that if the average value prevails, then radiation pressure in the sub-θ^1 Ori C region would be so large that hydrostatic equilibrium would exist and a variation of radial velocity with ionization state would not occur. One does see a velocity gradient there, although the absolute velocities are somewhat different from the rest of the nebula. From the existence of a velocity gradient even in the central region Ferland concludes that the smaller dust particles have been winnowed out by drifting through the ionized gas. The absorption component only being important, together with Ferland's arguments based on the otherwise inexplicable large velocity gradients, indicates that $A_V = 0.65$ would be a substantial overestimate.

Although this work only strengthens the idea that the Orion Nebula is indeed an optically thin layer of photoionized gas forming a blister on the front side of the Orion Molecular Cloud, one needs to remain wary of carrying the blister model too far, especially since there remain numerous fundamental questions (O'Dell 2001); but, one can safely argue that self-extinction is not the dominant process.

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