RevMexAA (Serie de Conferencias), **39**, 9–13 (2011)

REVIEW OF “THE LAW OF INTERSTELLAR EXTINCTION IN ORION” BY JOHNSON & MENDOZA (1964) AND ON “THE EXTINCTION LAW IN THE ORION NEBULA” BY COSTERO & PEIMBERT (1970)

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RESUMEN

Se reseñan los artículos “The Law of Interstellar Extinction in Orion” por H. Johnson y E. E. Mendoza, 1964, BOTT, 3, 25, 331 y “The Extinction Law in the Orion Nebula” por R. Costero y M. Peimbert, 1970, BOTT, 5, 34, 229. Cada reseña está precedida por una breve narración sobre la relación profesional entre los autores.

ABSTRACT

We review the papers “The Law of Interstellar Extinction in Orion” by H. Johnson and E. E. Mendoza, 1964, BOTT, 3, 25, 331 and “The Extinction Law in the Orion Nebula” by R. Costero and M. Peimbert, 1970, BOTT, 5, 34, 229. Each review is preceded by a brief account of the professional relationship between the authors.

Key Words: dust, extinction

1. INTRODUCTION

The editors asked us separately to review “The Law of Interstellar Extinction in Orion” by Johnson & Mendoza (1964) and “The Extinction Law in the Orion Nebula” by Costero & Peimbert (1970). However, since there is considerable overlap between these papers, it seems more appropriate to review them together.

2. CONTEXT

In a series of beautifully written papers, Trumpler firmly established the existence of interstellar dust (Trumpler 1930a,b,c). He also realized that dust is mainly concentrated towards the galactic plane and estimated both the selective extinction (reddening) and the total extinction. Extensive work culminated with a “Normal Extinction Law” (Whitford 1958), with $R_V \equiv A_V/E(B-V) \approx 3.1$.

Anomalous extinction was observed in a few regions, notably in the stars imbedded in the Orion Nebula first noticed by Baade & Minkowski (1937). Table 1 summarizes estimations of R_V in this region published prior to Costero & Peimbert (1970).

3. JOHNSON & MENDOZA (1964)

3.1. *The Authors*

Harold Johnson is one of the most important figures in modern observational astronomy, whose significant contributions to optical photometry and pioneering work in infrared photometry have been described by de Vaucouleurs (1995) and Low, Rieke, & Gehrz (2007). Eugenio Mendoza also specialized in stellar photometry and became one of the most influential Mexican astronomers of the 20th century (Chavarría 1994). They met at Yerkes Observatory in 1953, when Mendoza was a graduate student and took a summer course on photoelectric photometry taught by Johnson (Mendoza 1980). Mendoza visited Johnson several times, and in 1964 Johnson began to visit the Tonantzintla Observatory and the Instituto de Astronomía of the Universidad Nacional Autónoma de México (Mendoza 1980). Johnson’s involvement with Mexican astronomy deepened over the years; he accepted first a part-time position in the Instituto de Astronomía, UNAM in 1969 and eventually a full-time position in 1979, just before his death in 1980 (de Vaucouleurs 1995).

Johnson & Mendoza (1964) is the first of seven papers on which these authors collaborated. The 1960s papers deal with stellar photometry and interstellar extinction and the 1970s papers on stellar spectrophotometry obtained with the Michelson-Fourier spectrometer built by Johnson.

Equally importantly, both contributed to the search for a new site free from the light pollution that each year became worse at Tonantzintla. This search resulted in the current Observatorio Astronómico Nacional on Sierra San Pedro Mártir in Baja California (de Vaucouleurs 1995; Álvarez & López 1986; Moreno-Corral, Costero, & Schuster 1994).

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TABLE 1

EARLY DETERMINATIONS OF R_V IN ORION

Reference	R_V	Method[a]
Sharpless (1952)	6	VE
Johnson & Borgman (1963)	7.4	PSC+EX
Johnson & Mendoza (1964)	> 5	PSC+EX
Johnson (1965)	5.7	VE
Méndez (1967)	4.7	EC+PSC+RC
Johnson (1968a)	5	VE
Lee (1968)	> 5.5	PSC+EX
Gebel (1968)	5.5	EC+RC

[a]VE: Variable Extinction (in galactic clusters, yielding the true distance modulus and R_V); PSC: Paired Stellar Comparison (color excess); EX: Extrapolation to $1/\lambda = 0$; EC: Emission-line Comparison (in H II regions); RC: Radio continuum.

Johnson also helped negotiate an agreement with the University of Arizona to bring to San Pedro Mártir the 1.5 meter photometric telescope he had designed and built for the Catalina Station of the Lunar and Planetary Laboratory (Johnson 1968b; Álvarez & López 1986; Moreno-Corral, Costero, & Schuster 1994). This telescope was installed in 1970 and was the first large telescope at the new observatory. It served first for photometry and then also for direct imaging, after its aluminum alloy primary mirror was replaced with a Cer-Vit mirror and a CCD detector was acquired. The telescope was named after Johnson following his death. It is currently being converted for robotic operation with a multi-channel *riZYJH* imager.

3.2. *The Paper*

The paper presents spectroscopy and *UBVRIJK* photometry of an early-type star in NGC 2024 and an estimation of the extinction to the star using the "pair method". That is, by comparing photometry of a reddened program star to photometry of an unreddened standard star (or set of standard stars).

NGC 2024 is a H II region, more imaginatively known as the Flame Nebula. It lies slightly to the east of ζ Ori, the eastern-most star in Orion's belt, and is associated with the Orion B molecular cloud. Guillermo Haro had mentioned a star in NGC 2024 to Johnson and Iriarte, suggesting that it might be an early-type star with higher extinction than the Trapezium stars. The coordinates of the star are 05 41 37.85 − 01 54 36.5 (J2000) in the 2MASS point source catalog (Cutri et al. 2003). Johnson & Iriarte referred to the star as "NGC 2024 No. 1", but it was subsequently renamed "IRS1" by Thompson, Thronson, & Campbell (1979), and this latter name has stuck. The star is visually one of the brightest stars in the nebula (see Figure 1a) and was suspected of being its principal ionizing star. A spectrum obtained by Johnson and Iriarte with the newly-commissioned 1.0 meter telescope at Tonantzintla confirmed that it was "a typical OB star". Garrison (1968) later reported a spectral type of B0.5 Vp. However, subsequent studies suggest that the dominant ionizing source is the more deeply embedded star IRS2 (Gordon 1969; Bik et al. 2003; see Figure 1b).

Johnson & Iriarte obtained *UBVRIJK* photometry from Tontantzintla Observatory and the Catalina Observatories, which showed that the star was bright and very red, with $K \approx 5.8$ and $V - K \approx 6.3$. This photometry was obtained in the early years of modern infrared photometry; Johnson had only built and begun to use his PbS photometer, responsive from 1 μm to 3.5 μm, in late 1961 or early 1962 (Low, Rieke, & Gehrels 2007) and had only just published his first compilations of photometry of normal stars (*KL* in Johnson 1962; *JKLMN* in Johnson 1964). Johnson did not adopt Becklin's *H* filter until much later (Johnson, MacArthur, & Mitchell 1968).

The extinction law was determined by comparing the photometry to unreddened supergiants between B1 and F0. It was insensitive to the choice of the comparison star, which is not surprising as the *BVRIJK* colors of OBA stars are similar. The star was found to have $E(B - V) \approx 1.7$, signifi-

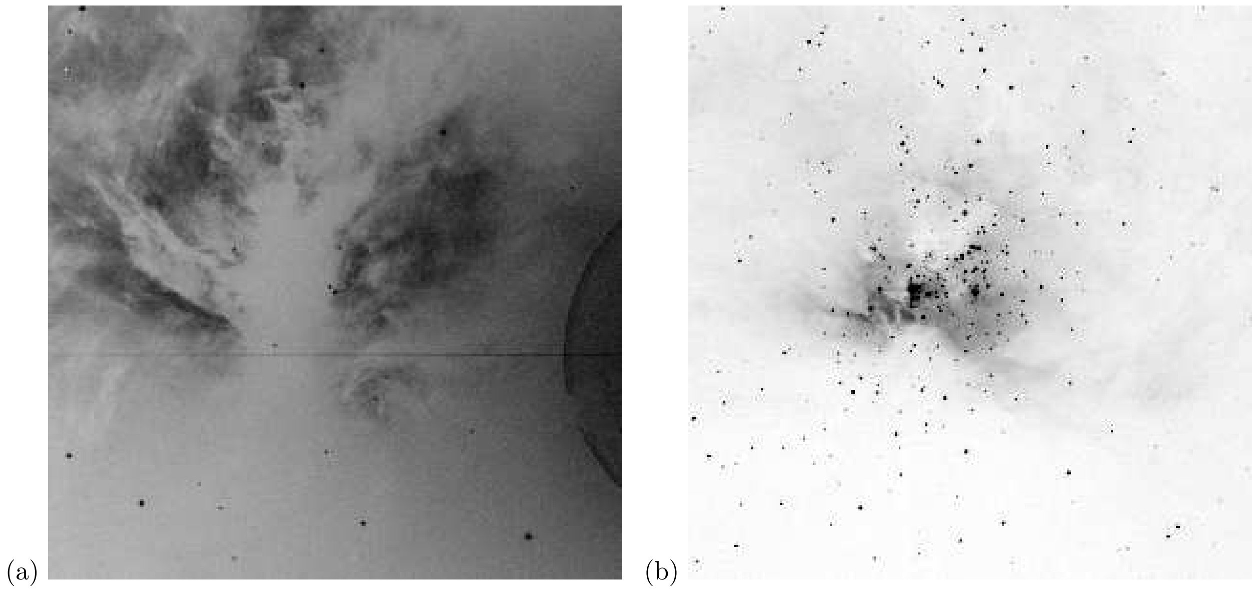

Fig. 1. (a) DSS2 blue and (b) 2MASS K images of NGC 2024 centered on IRS1. The images are 18 arcmin to a side. The ionizing star IRS2 is the brightest source in the 2MASS image; IRS1 is a few arcmin to the west of IRS2 and is the bright star seen on the edge of the dark lane in the DSS2 image. The extremely bright star to the west of the image is ζ Ori.

cantly larger than the 0.3–0.4 of the Trapezium stars. When normalized by $E(B-V)$, the reddening curve lay between the "normal" Cygnus and Orion curves determined by Johnson & Borgman (1963).

The contribution of this paper was not that it was the first determination of the infrared extinction law, as it had been preceded by Johnson & Borgman (1963), but that by measuring the extinction law towards a heavily obscured star using a standard method, it laid to rest any remaining doubts about systematic errors in determinations from less obscured stars.

4. COSTERO & PEIMBERT (1970)

4.1. *The Authors*

Manuel Peimbert and Rafael Costero met at the Secundaria Diurna #3 "Héroes de Chapultepec", a public junior high school at Mexico City, which they attended from 1953 to 1955. Their first research collaboration (Peimbert & Costero 1961), about their finding of a dozen new Galactic planetary nebulae, was published while they were college students at the Facultad de Ciencias of the Universidad Nacional Autónoma de México. They later worked together on a paper on chemical abundances in H II regions (Peimbert & Costero 1969), which is also reviewed in this issue. This paper is the source of the hydrogen emission lines strengths used in Costero & Peimbert (1970) to study the extinction law in the direction of the Nebula. They have collaborated on one other paper, a catalogue of Galactic O-stars, which analyses the contribution of hot stars, located outside dense H II regions, to the ionization of the low density interstellar medium.

4.2. *The Paper*

Costero & Peimbert (1970) compared the Balmer (H9, Hδ, Hγ, Hβ, Hα) and Paschen (P9, P7, P6) hydrogen line ratios, observed in four regions in the Orion Nebula (including M42 and M43) by Peimbert & Costero (1969), with theoretical computations for Case B by Pengelly (1964). The extinction curve at 9 points in the 3835–10938 Å spectral interval was thus derived. Additionally the total extinction at Hβ was obtained by comparing the ratio of the absolute flux of this line, as measured in each of those regions, to flux the 1.95 cm radio-continuum flux, as integrated over the corresponding region in the contour map by Schraml & Mezger (1969), with the same ratio derived from theoretical computations for the emissivity of Hβ (Pengelly 1964) and for the free-free nebular emission by Oster (1961).

The average extinction curve so obtained yields $R_V = 5.5 \pm 0.7$, in excellent agreement with the values previously derived from the variable extinction method, which is independent of photometric infrared excesses now known to strongly affect the PSC+EX method. In fact, the authors find that there is additional emission in the K and L bands, at the observed Orion Trapezium Cluster stars, which is responsible for the larger R_V values obtained from the extrapolation method. They conclude that this infrared excess is probably due to re-radiation by circumstellar hot dust and nebular free-free emission.

Variations in the extinction law between the four observed regions is suspected, but the observational errors preclude the authors of any firm conclusions. However, marginally different values of R_V, as compared to those close to the Trapezium, are found: a larger value in the region close to θ^2 Ori B, and a smaller one near HD 37061 (M43). In order to gain precision and avoid interpolation in the extinction curve, a more adequate total-to-selective extinction ratio, $R_H = A_{\mathrm{H}\beta}/E(\mathrm{H}\beta, \mathrm{H}\alpha)$, is defined in the paper. This ratio is equal to 2.7 in the "normal" extinction law (Seaton 1960) and its value in the Orion Nebula is found to be very similar (3.5 ± 0.3) in three of the observed regions, and somewhat higher (4.4 ± 1.1) in the region 35 arcsec north of θ^2 Ori B.

5. SUBSEQUENT WORK

5.1. *Variations in Extinction*

Johnson & Mendoza noted that "while the extinction curves for these regions differ greatly in the infrared, they are virtually identical in the (U, B, V) region". We now believe that the infrared extinction law is almost constant and the most significant variations occur below 0.9 μm (Jones & Hyland 1980; Koorneef 1983; Rieke & Lebofsky 1985; Cardelli, Clayton, & Mathis 1989). The apparent variation in the infrared seen by Johnson & Mendoza arises spuriously by normalizing the extinction to $E(B-V)$, which lies in the variable part of the curve, rather than a quantity that depends only on the infrared part of the curve (e.g., A_J or $E(J-K)$). As observational errors have become ever smaller, slight but real variations in the near infrared extinction law have finally been detected (Larson & Whittet 2005; Nishiyama et al. 2006; Froebrich et al. 2007; Gosling, Bandyopadhyay, & Blundel 2009; Fitzpatrick & Massa 2009).

5.2. *Potential Pitfalls of the Emission-Line Method*

Mathis (1970, 1983) has pointed out some potential problems inherent to the EC+RC method to determine the extinction law: the value of R_V (and R_H) will be spuriously increased by the presence of dust within or behind the observed ionized region –due to wavelength-dependent dispersion and albedo properties– and by possible background radio-continuum emission arising from highly obscured, and maybe even optically-thick, ionized regions. However, in the case of the Orion Nebula, most of the interstellar extinction occurs in a foreground veil (see, e.g., O'Dell 2001) and the fact that essentially identical values of R_V are found from both the differential extinction method and the emission-line plus radio-continuum method, is a good indication that these pitfalls are probably negligible in the case of the Orion Nebula region.

5.3. *Other Applications of the Emission-Line Method*

Many people use optical recombination lines and radio continuum to determine the extinction at a single wavelength (e.g., O'Dell & Yusef-Zadeh 2000). However, using multiple recombination lines to determine extinction laws is not common. Noticeable exceptions are the work by Greve et al. 1994 –where pairs of "corresponding" lines (arising from the same upper state) and the Balmer decrement are used for the Orion Nebula– and the very complete study by Blagrave et al. (2007), also in Orion, who use recombination lines of both H and He –the latter modeled to correct their theoretical ratios for radiation transfer problems– expanding the spectral coverage to the UV range. These works essentially confirm and refine Costero & Peimbert's results, and reconcile the stellar continuum with the nebular line methods to determine "anomalous" extinction laws, at least in the Orion Nebula.

To our knowledge, the EC+RC method has not been applied to any other H II region except the Orion Nebula. This probably because of the possible pitfalls mentioned above. Nevertheless, existing high spatial resolution radio-frequency observations (comparable to that in the optical ranges), modern optical and infrared detectors, and high spectral resolution technologies could probably contribute to determine if there are spatial variations in the reddening law towards Orion and, if so, to better understand the processes of dust formation and destruction (see, e.g., Cardelli & Clayton 1988).

5.4. *The Origin of the Anomalous Extinction*

"Anomalous" extinction curves like that of Orion are known to exist towards other clouds, as deduced from the stars embedded in the nebulae. The changes in extinction law are thought to be a result in grain processing between the diffuse ISM ($R_V \approx 3.1$) and denser clouds ($R_V \approx 5.5$ for typical "outer cloud dust"), with grain coagulation being the dominant effect (Mathis 1990).

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