RevMexAA (Serie de Conferencias), **39**, 83–86 (2011)

COMMENTARY ON THE PAPER "THE H-R DIAGRAMS OF YOUNG CLUSTERS AND THE FORMATION OF PLANETARY SYSTEMS" BY POVEDA (1965)

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RESUMEN

Presento una reseña del artículo de A. Poveda, 1965, BOTT, 4, 26, 15 donde él discute desde un punto de vista teórico las características esperadas de una estrella en formación. Motivado originalmente por tratar de explicar dos enigmas aparentes de la formación estelar, la existencia de estrellas jóvenes por debajo de la secuencia principal y la paradoja de Faulkner-Griffiths-Hoyle, el artículo pasa a predecir fenómenos que fueron luego confirmados observacionalmente y que constituyen parte medular del entendimiento contemporáneo de la formación estelar y planetaria.

ABSTRACT

I present a review on the paper by A. Poveda, 1965, BOTT, 4, 26, 15, where he discusses from a theoretical point of view the expected characteristics of a forming star. Originally motivated to explain two apparent puzzles of star formation, the existence of young stars below the main sequence and the Faulkner-Griffiths-Hoyle paradox, the paper went on to predict phenomena that were later confirmed observationally and that constitute important part of our present knowledge of stellar and planetary formation.

Key Words: Herbig-Haro objects — ISM: jets and outflows — stars: formation — stars: pre-main sequence

1. INTRODUCTION

The field of star formation has developed mostly in the last few decades. If we use the SAO/NASA Astrophysics Data System (ADS) to find how many papers had been published up to 1965 that had the words "star" and "formation" in its abstract, we get only 893 entries. In contrast a similar query up to the date when this paper was written (October 2010), produces more than 100,000 abstracts. The literature of this field has expanded by a factor of a thousand over the last 45 years!

Among the papers published in 1965 is this contribution written by Arcadio Poveda. Then a theoretical astronomer in his mid-thirties, Poveda considered the handful of observational evidence related to star formation then available and made a model and a number of predictions that were well ahead of its time.

2. THE MOTIVATION OF THE POVEDA PAPER

Following Poveda (1965), we find that his paper was motivated by two puzzling facts known at that epoch. The first was the existence of young stars below the main sequence and the second was the so called Faulkner-Griffiths-Hoyle paradox.

By 1965 it was well established, in particular by Hayashi (1961), that the evolutionary track for young contracting stars should exist above the main sequence, since for a given temperature they were overluminous with respect to their main sequence luminosity. However, examples of young stars below the main sequence were known (e.g., Herbig 1962). How could this discrepancy be explained? The second fact that motivated Poveda was that, as mentioned before, in the Hayashi track (the pre-main-sequence track followed by young solar-type stars), the stars were predicted to be fully convective and much more luminous than in the main sequence. This higher luminosity and a very strong solar flare activity was expected to produce that the planetesimals could not have retained significant amounts of water. However, there is water on Earth. This was known as the Faulkner-Griffiths-Hoyle paradox (Faulkner et al. 1963).

3. THE MODEL

Poveda proposed a model in which the contracting star was surrounded by an envelope of gas and dust that would first evolve into a disk and later into planets, that could account for the two facts described in the previous section and allowed the ex-

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© 2011: Instituto de Astronomía, UNAM - Highlights of Boletín de los Observatorios de Tonantzintla y Tacubaya
Ed. S. Torres-Peimbert & O. López-Cruz

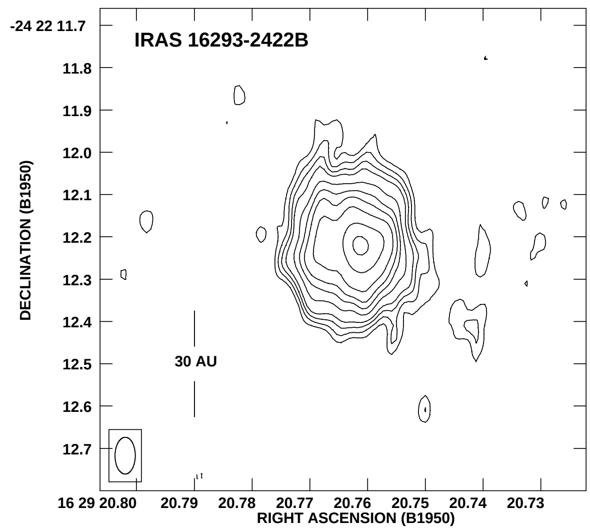

Fig. 1. VLA image at 7 mm of the disk associated with the forming star IRAS 16293-2422B. Contours are −3, 3, 4, 5, 6, 8, 10 ,12, 15, 20, and 25 times 0.1 mJy beam^{-1}, the rms of the image. The half power contour of the synthesized beam ($0''.09 \times 0''.05$; PA = 0°) is shown in the bottom left corner. Data from Rodríguez et al. (2005).

planation of other observed phenomena and even the prediction of unobserved ones.

In this scheme, it was expected that the dust grains in the envelope would grow to sizes much larger than the wavelength of visible light and that then its absorption would be "grey" (independent of wavelength). This will make the observed position of young stars "descend" vertically in the H-R diagram until some could appear to be below the main sequence. Furthermore, the shielding provided by this dust could have allowed the planetesimals to remain cooler than expected and to retain its water (in the form of ices). One aspect that was not considered here is that the radiation absorbed by the dust would be re-radiated and that even when the planetesimals were not exposed to the direct light of the Sun, they would receive the same amount of luminosity from the surrounding dust, although at lower photon energies.

Pleased with these results, Poveda went on to consider other known phenomena and to make predictions that could be observed in the future. He reached four main additional conclusions.

3.1. *Young stars as bright infrared sources*

Poveda reasoned that the original visible radiation from the surface of the star would be absorbed by the dust in the surrounding envelope and re-radiated in the infrared. Specifically, he predicted that *"...it should be possible to find bright infrared stars with effective temperatures around 400 K"*. This was a major prediction that, in one of the golden moments of mexican astronomy, was soon confirmed observationally by a mexican observer, Eugenio Mendoza (1966). These results led to the beginning of the industry of infrared observations of young stars (Johnson 1967) where an inmense number of studies have been published (e.g., Zuckerman 2001).

The infrared emission, as well as the emission at millimeter wavelengths (e.g., Rodríguez et al. 2005; see Figure 1), originates in disks that surround the forming star. At present it is believed that the disk is heated both by the stellar radiation as well as by the viscous dissipation of energy in the disk (D'Alessio et al. 1998).

3.2. *High frequency of planetary systems*

In the model of Poveda, the envelope of gas and dust around the forming star would undergo important evolutionary effects. First, the dust grains will stick together and become larger to produce the grey absorption required to account for the existence of young stars below the main sequence. Later, the envelope, more or less spherical, would become disk-shaped and finally it would transform into planets. So, he proposed that *"If the existence of these infrared stars is confirmed, one would also have proved the high frequency of planetary systems"*. Indeed, infrared emission is a characteristic of young stars and in this scheme planetary systems are expected to be common. But, in 1965 there simply was no observational way to test if other stars have planets around them. This changed dramatically 30 years after, with the detection of the first exoplanet (Mayor & Queloz 1995). More than 500 exosolar planets are known at present and the chase is now for a terrestrial-like exoplanet (e. g. Vogt et al. 2010).

3.3. *The nature of the Herbig-Haro objects*

Another puzzle related to star formation was the existence of the enigmatic Herbig-Haro (HH) objects (Herbig 1951; Haro 1952) in regions of star formation. The HH objects are bright optical nebulosities that appear in the surface of the molecular clouds where star formation is taking place. They lack an internal source of energy, so what was exciting them remained poorly understood for decades. Poveda, discussed the HH object (Burnham's nebula) near the star T Tau and concluded that it had to be excited remotely. How to achieve this? The transformation of the envelope around the young star

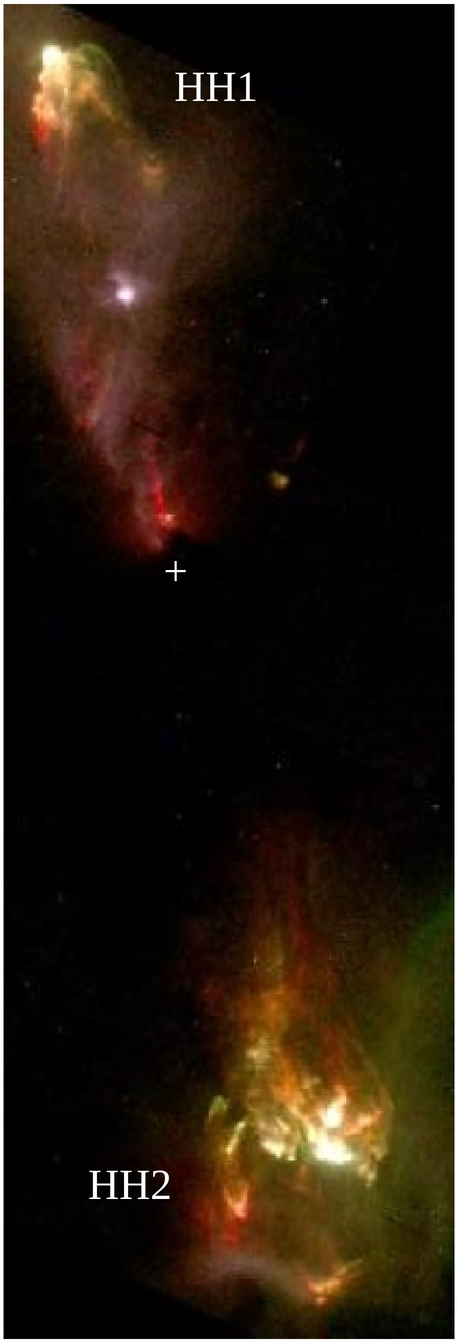

Fig. 2. HST image of the HH objects 1 (top) and 2 (bottom). The cross at the center marks the position of the embedded star, detected in the radio by Pravdo et al. (1985), that excites both HH objects. The image has been rotated for easier display and is courtesy of NASA.

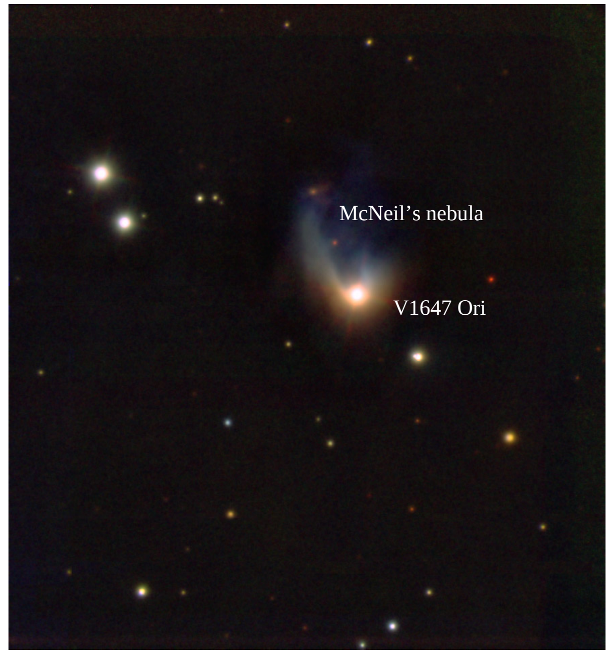

Fig. 3. JHK color composite LIRIS image of V1647 Orionis and the associated McNeil's Nebula. This star has been proposed as the most recent FU Orinis object, although its characteristics favor that it belongs to the class of EXor eruptive variables. Image courtesy of LIRIS project.

in a disk would provide a preferential axis of rotation along which a flow of collimated particles could emerge and travel by the interstellar space to remotely excite the HH objects. In Poveda's words: *"...corpuscular radiation begins to leak about the axis of rotation... along two opposite cones. If within these cones there happen to lie appropriate dense globules, they will begin to shine..."* This is a completely modern version of the HH objects that took several decades and the work of many astronomers to consolidate. In particular, the detection of diverging proper motions in the first HH objects detected, HH1 and HH2, by Herbig & Jones (1981) and the posterior detection in between the two HH objects of the embedded star (Pravdo et al. 1985) gave strong support to this picture (see Figure 2). The HH objects have been reviewed by Reipurth & Bally (2001).

3.4. *The nature of the FU Ori objects*

Poveda did not do as well is his fourth prediction, related to the FU Ori stars. These are pre-main-sequence eruptive variables where a large increase (up to factors of $\sim$100) in optical brightness takes place over a period of months and is followed by a slow decrease over years or decades (Hartmann & Kenyon 1996).

Poveda (1965) proposed that the transformation of the envelope into a disk and the clearing produced by the formation of planets could suddenly "clear up" the embedded star and produce an apparent brightening. However, as discussed by Cruz-González (2011) at present it is believed that the FU Ori phenomenon is produced by a large increase in the accretion rate of the disk and the consequent growth in luminosity (Hartmann & Kenyon 1996). In other words, the increase in brightness is intrinsic to the source (an increase in the accretion rate) and not extrinsic (the removal of an obscuring screen).

FU Ori systems imply that disk accretion in early stellar evolution is highly episodic, varying from $\sim 10^{-7}$ $M_\odot$ yr^{-1} in the low (T Tau) state to $\sim 10^{-4}$ $M_\odot$ yr^{-1} in the high (FU Ori) state. This variability in mass accretion is matched by a corresponding variability in mass ejection, with mass loss rates reaching $\sim$0.1 of the mass accretion rates in outburst.

Only about 10 so-called "classical" FUors (those that have been directly observed to optically brighten over a period of a few weeks to a few months) have so far been found. It has been speculated that V1647 Ori, associated with McNeil's nebula (see Figure 3), is the most recent such object (Aspin et al. 2009). However, the characteristics of this source suggest it most likely is in the "EXor" class of eruptive variables, named after their class progenitor, EX Lupi (Herbig 2008).

4. WHAT HAPPENED WITH THE ORIGINAL MOTIVATIONS?

We mentioned that Poveda's paper was originally motivated by two puzzling facts: the existence of young stars below the main sequence and the Faulkner-Griffiths-Hoyle paradox. How do we see these problems nowadays?

The existence of young stars apparently below the main sequence is most probably a result of the fact that accretion into the star can produce ultraviolet excesses (Kenyon & Hartmann 1995). This will move a low luminosity young star from the right to the left of the H-R diagram (since it becomes "bluer") and put it apparently below the main sequence track.

It is still believed that planetesimals go through a hot phase given the large luminosities expected from the pre-main-sequence Sun. So, why do we have water on Earth when it should have sublimated from the planetesimals? It has been proposed that comets, trans-Neptunian objects or water-rich meteorites from the outer reaches of the Solar System (where it never got as hot as at the position of the Earth) may have deliverd water to the Earth, but the debate is still open (Kasting & Catling 2003).

5. CONCLUSIONS

As happened with several papers published in the Boletín de los Observatorios de Tonantzintla y Tacubaya (BOTT), this paper did not receive the attention it deserved. At present it has 30 citations in the ADS. One can only speculate that in the pre-internet era the distribution of the BOTT reached a limited number of astronomers. The situation is very different at present with the Revista Mexicana de Astronomía y Astrofísica, that is immediately included in the ADS and is found when a query on a given topic is sent. Some of the characteristics of BOTT may have also difficulted reaching a larger audience. In Poveda's paper the abstract appears only in spanish (although the text is in english). The lack of an abstract in english probably discouraged the casual reader. Again the Revista has corrected this, including abstracts both in spanish and in english.

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