RevMexAA (Serie de Conferencias), **15**, 275–280 (2003)

PLANETARY NEBULAE, BUBBLES, AND SUPERBUBBLES: WHAT CAN WE LEARN FROM THEIR KINEMATICS?

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RESUMEN

Presentamos tres ejemplos que ilustran cómo la confrontación entre la información derivada de la cinemática de nebulosas planetarias, burbujas y superburbujas y los modelos teóricos que describen su evolución nos permite tener una mejor comprensión sobre los mecanismos físicos involucrados en el orígen y evolución de estos objetos y en idear mejores métodos de observación.

ABSTRACT

We present three examples on how the confrontation between the information we can derive from the kinematics of planetary nebulae, bubbles, and superbubbles and the theoretical models of evolution of these objects allows us to have a better understanding of the physical mechanisms involved in the creation and evolution of these objects and to conceive better ways to observe them.

Key Words: **GALAXIES: ISM — GALAXIES: IRREGULAR — ISM: BUBBLES — ISM: KINEMATICS AND DYNAMICS — PLANETARY NEBULAE: GENERAL**

1. INTRODUCTION

Planetary nebulae (PNe), bubbles and superbubbles are nebular structures formed by the interaction between the fast winds of stars in their present evolutionary stage and the interstellar (ISM) or circumstellar (CSM) medium. In all these cases, an expanding shell is formed as a result of the formation of two shocks, separated by a contact discontinuity: one shock in the fast wind and the other shock in the ISM or the ejected CSM. In this context, the study of the kinematical properties of the shells is of particular importance in order to confront the observations with the theoretical evolutionary models of PNe and wind-blown bubbles.

This work addresses three different aspects of the same problem: (1) the kinematical study of the ionized and molecular gas in bipolar PNe in our Galaxy, (2) the search for wind-blown bubbles around massive, isolated stars in the Large Magellanic Cloud (LMC), and (3) the effects that winds from massive stars cause in the ISM of some galaxies like the irregular galaxy IC 1613.

2. A QUICK HISTORICAL OVERVIEW OF THE THEORETICAL MODELS FOR "BUBBLES"

Pikel'ner (1968), motivated by Courtès (1960), Sheglov (1963) and Johnson & Hogg's (1965) discoveries of high-velocity gas (up to 70 to 100 $\mathrm{km\,s^{-1}}$) in several diffuse nebulae, in particular, around Wolf-Rayet (WR) stars, formally established for the first time the idea of a thin nebular shell formed of two layers: the shocked stellar wind and the shocked ambient medium separated by a contact discontinuity. He wrote the equations and obtained numerical solutions for the shell velocity as a function of radius. However, he did not examine the timescale of the motion. In independent ways, but simultaneously, Dyson & de Vries (1972) and Avedisova (1972) obtained similarity solutions to this flow pattern. The paper of Dyson & de Vries (1972) has the merit of definitely settling what is now known as the "classical" model of wind-blown bubbles; in the words of Dyson & de Vries:

> "The fast-moving stellar wind encounters effectively stationary nebular gas. An outward facing shock must therefore form ahead of the leading edge of the stellar wind gas. The stellar wind gas will be sharply decelerated by the shell of shocked nebular gas, and an inward facing shock will form in the stellar wind. A contact discontinuity will, in principle, separate the shocked nebular and shocked stellar wind regions."

Figure 1, adapted from Dyson & de Vries (1972), shows the flow pattern of the classical model. Further developments of this model have been done by Falle (1975) and, in the paper of Weaver et al. (1977), a comprehensive study of the flow pattern and of its

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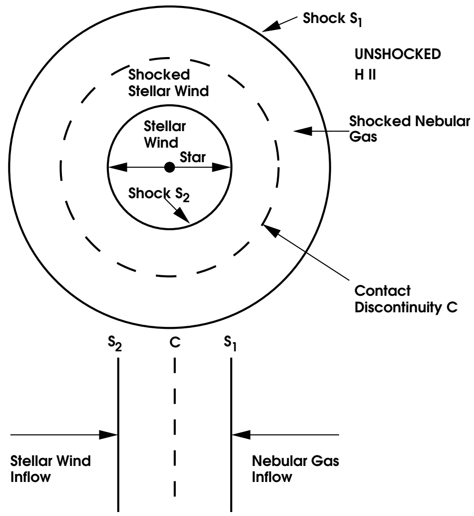

Fig. 1. The idealized flow pattern of the bubble model of Dyson & de Vries (1972).

implications was established. It is also important to stress that analytic (such as the self-similar) solutions are the kind of predictions that observers are looking for in order to compare with the data. We will discuss some of the implications of the classical model in § 5 and 6. The self-similar solution of the classical model was conceived for fast winds interacting with an infinite ambient medium of uniform density; in that case, the shell velocity decreases with time. However, when the ambient medium is the result of a previous ejection of mass (as in the case of PNe or some bubbles around WR stars) and this medium is moving, then, basically the flow pattern established in the classical model holds but the flow equations and solutions are different for they take into account the motion of the ambient medium and the geometrical dilution of the ejected medium as it expands. Indeed, self-similar solutions have been found by Kwok, Purton, & Fitzgerald (1978) and Kwok (1982) and applied to PNe, implying that the shell expands at constant velocity. This is the "colliding winds model" for PNe that, as we have seen, has been inspired by the flow pattern settled by Pikel'ner (1968), Dyson & de Vries (1972) and Avedisova (1972).

3. OBSERVATIONS

3.1. *Observations of Molecular and Ionized Gas in Bipolar PNe*

We have developed two instruments which use scanning Fabry-Perot (FP) interferometers in order to obtain the radial velocity profiles at every point within the whole extent of a nebula or galaxy. The observations were carried out with the 2.1 m telescope of the Observatorio Astronómico Nacional at San Pedro Mártir, B.C., México (OAN-SPM). To study the molecular gas we are developing PUMILA, which uses a scanning FP interferometer optimized in the near IR (see Rosado et al. 1999 and Arias et al. 2001). It has been used to obtain velocity cubes of the line at 2.12 μm of molecular hydrogen, corresponding to the v = 1–0 rotational transition. To study the emission lines of the ionized gas we have developed the UNAM scanning FP interferometer PUMA (Rosado et al. 1995), optimized in the red, which allows us to obtain velocity cubes at Hα, [N II] λ 6583 Å, [S II] λ 6717 and 6731 Å and [O III] λ 5007 Å. The sampling spectral resolutions of the FP interferometers are about 10 and 20 km s^{-1} for the IR and visible, respectively.

3.2. *Observations of Bubbles around Isolated O Stars*

The work of Nazé et al. (2001) includes images taken with the *Hubble Space Telescope* (*HST*) WFPC2, and high-dispersion echelle spectra taken with the CTIO 4 m telescope. The spectral resolution is about 13 km s^{-1}.

3.3. *Observations of Superbubbles in IC 1613*

The observations were carried out with the PUMA instrument mentioned above attached to the 2.1 m telescope of the OAN-SPM. Velocity cubes at Hα and [S II] λ 6717 and 6731 Å of the entire optical emission of the galaxy have been obtained.

4. SHOCKS IN THE MOLECULAR ENVELOPES OF BIPOLAR PLANETARY NEBULAE

Molecular gas has been detected in some PNe by Treffers et al. (1976) who detected the line of the S(1) v = 1–0 transition of H_2 at 2.12 μm (i.e., in the near-IR). Surprisingly enough, no survey at radio wavelengths has been conducted in order to study the kinematics of the CO molecule at high angular resolution. In the case of the near-IR, it was just recently, with the development of 2-D detectors, that imaging in the lines of H_2 revealed the detection of extended H_2 emission, mainly in bipolar PNe. According to theoretical models, bipolar PNe are the result of a non-uniform distribution of material ejected by the central star while it passes through the AGB phase. Consequently, the study of the kinematics of molecular gas in PNe could give important insights on how the ejection is accomplished, on the amount of ejected gas and timescales. The observations of the interrelation between ionized and molecular gas in PNe could serve to know whether the "colliding winds" model proposed by Kwok et al. (1978) describes reality, or not.

One of the key problems concerning the near-IR H_2 emission lines is the discrimination of the excitation mechanism. Indeed, since the H_2 molecule is monopolar, its emission lines in the IR are due to vibration-rotation or pure rotation transitions of excited energy levels. However, it is not clear whether the energy levels are populated by radiative pumping (fluorescence) or by collisions (shocks). This is still an open question. Usually, the way to discriminate between shocks and fluorescence is to observe lines corresponding to several energy levels and construct "excitation diagrams" to be compared to theoretical models of shocks and fluorescence (Burton 1992). In the case of the faint emission of the H_2 lines in PNe, only spectra integrated over the whole extension of the nebula have been obtained and their implications could be misleading for a series of reasons. An easier, but not safe enough, way is to consider the ratio between the S(1) 2–1 (at 2.24 μm) and S(1) 1–0 (at 2.12 μm) lines . When this ratio is much less than 0.5 it indicates shock excitation. We have conceived an independent way of discrimination using the kinematics of the H_2 line at 2.12 μm. If we are able to measure expansion velocities in the molecular gas larger than the sound speed of the medium, then we can show that the molecular gas is shocked.

As part of her PhD thesis, Lorena Arias is studying the interrelation between ionized and molecular gas in PNe focusing mainly on the kinematics of H_2 2.12 μm line, for the molecular gas, and on the lines of Hα, [N II], [S II], and [O III] of the ionized gas. The details of the observations are given in § 3.1.

Here we only discuss the case of the bipolar PN NGC 2346 (Arias et al. 2001). This PN is formed of a bright torus and two elliptical lobes. The kinematics of the ionized gas was obtained long ago by Walsh, Meaburn, & Whitehead (1991) while that of the CO torus was reported in Bachiller et al. (1989).

We have obtained direct images in the H_2 lines at 2.12 μm and 2.24 μm, which show that the ratio between the lines S(1) 2–1 and S(1) 1–0 is much smaller than 0.5, suggesting shock excitation. Furthermore, we have obtained flux-calibrated FP velocity cubes in the H_2 2.12μm line, which allow us to measure the shock velocities of the H_2 and to propose a geometrical model for the H_2 emission.

In Figure 2 (from Arias et al. 2001) we show typical radial velocity profiles of the H_2 emission line at 2.12 μm superimposed on the image of NGC 2346 emission at 2.12 μm. Since our FP velocity cubes allow us to obtain radial velocity profiles of each pixel over the whole extension of this PN, we are able to obtain position-velocity diagrams that could be used to fit a geometrical model. Figure 3 (Arias

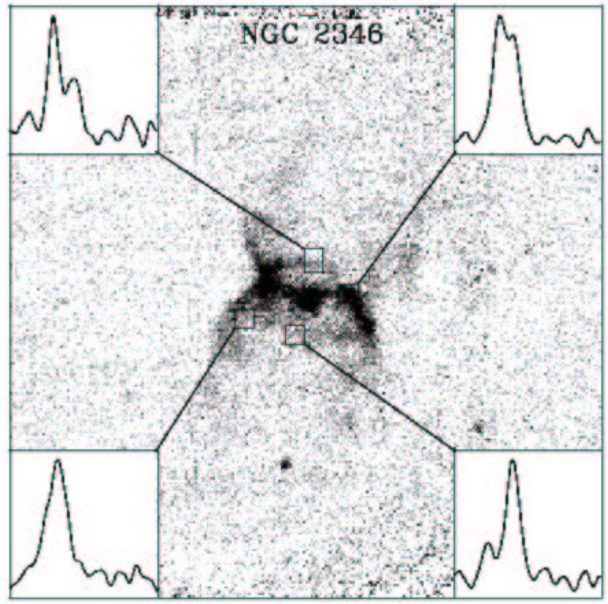

Fig. 2. Typical radial velocity profiles of the molecular gas in NGC 2346 in the H_2 line at 2.12 μm superimposed on a direct image in the same line (from Arias et al. 2001).

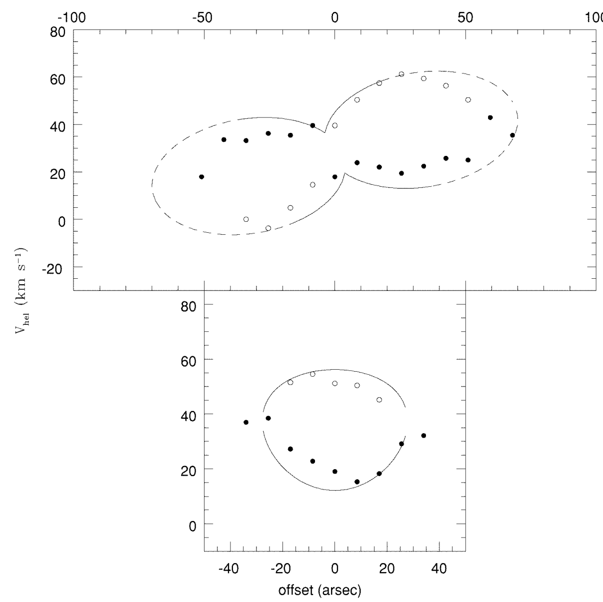

Fig. 3. Observed (dots) and predicted model (solid lines) position-velocity diagrams obtained for the velocity field of the shocked H_2 in NGC 2346, along the major axis (top) and across it (bottom), from Arias et al. (2001).

et al. 2001) shows the position-velocity diagrams along and across the major axis of the bipolar nebula and the solid lines are the predictions of the selected geometrical model: two thin, ellipsoidal, closed shells with a velocity law increasing with distance from the PN nucleus. We were able to derive the inclination angle (30°) and the expansion velocity at the torus ($16\,\mathrm{km\,s^{-1}}$) and in the lobes (up to $60\,\mathrm{km\,s^{-1}}$ at the ends). Expansion velocities this high are supersonic and consequently we have shown, by independent means, that the excitation mechanism of the H_2 molecule in NGC 2346 is shocks. On the other hand, it was found that the kinematics of the ionized and molecular gas (both H_2 and CO) are quite similar.

An important issue is to estimate the mass of the H_2 gas from the H_2 kinematics. Using a Boltzmann population distribution we can obtain the mass of the shocked H_2. We obtained that the mass of shocked H_2 in the torus is $1.29 \times 10^{-4} M_\odot$. But the shocked H_2 is in a thin sheet enveloping the unshocked H_2. In order to estimate the mass of the molecular torus we obtained the pre-shock density, n_0, using $n_0 = S_{1\text{–}0}(V_\mathrm{s})^{-1.7}$, (Kwan 1977), where $S_{1\text{–}0}$ is the surface brightness of the $2.12\,\mu$m line, the shock velocity $V_\mathrm{s} = V_\mathrm{exp} - V_\mathrm{rg}$, and the velocity of the ejected ambient medium is V_rg. Assuming that the ambient medium comes from an isotropic ejection during the red giant phase of the exciting star and that $V_\mathrm{rg} = 5\,\mathrm{km\,s^{-1}}$, we obtain an estimate of $0.6\,M_\odot$ for the mass of the unshocked H_2 in the torus. This is an independent way of estimating the mass of molecular PN envelopes. In the case of NGC 2346 this mass estimate points towards a massive progenitor, as was found by Corradi & Schwarz (1995) using very different arguments.

5. SEARCH FOR BUBBLES AROUND ISOLATED O STARS

The classical model for wind-blown bubbles has a series of predictions:

- All massive stars with fast stellar winds should be surrounded by bubbles.
- The wind luminosity L_w can be estimated from bubble parameters, i.e.,

$$L_\mathrm{w} = f(n_\mathrm{amb}, V_\mathrm{shell}, R_\mathrm{shell}),$$

where n_amb is the electron density of the ambient medium, V_shell and R_shell are the bubble expansion velocity and radius, respectively.

- The dynamic timescale can also be estimated from the bubble expansion velocity and radius.

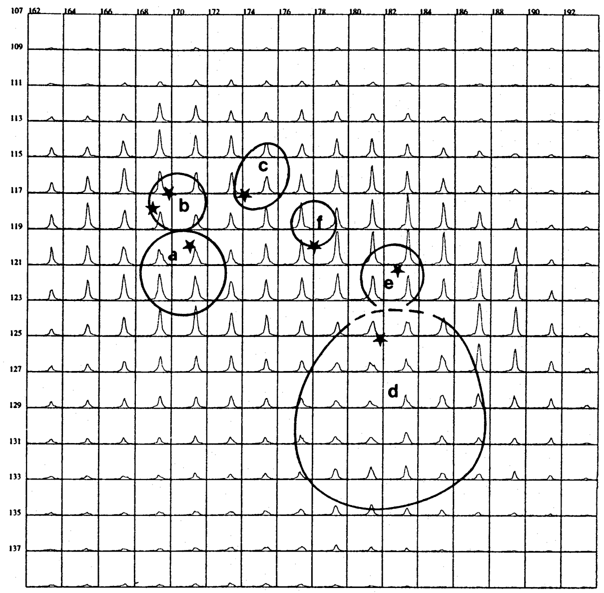

Fig. 4. Kinematical evidence of bubbles around individual OB stars in LH 10 (from Rosado et al. 1996).

- At the interface between the shocked fast wind and the outer nebular shell, heat conduction lowers the temperature and mass evaporation raises the density of the shocked fast wind, producing optimal conditions for soft X-ray emission (this last prediction is discussed in Chu, Gruendl, & Guerrero 2003).

At least two important problems arise when observations are compared to theoretical models: (1) the diffuse X-ray luminosities of the Galactic WR nebulae NGC 6888 and S 308 are at least an order of magnitude lower than the theoretical predictions (Wrigge, Wendker, & Wisotzki 1994; Wrigge 1999) (2) no ring nebulae around main-sequence O stars have been reported so far (Chu 1991; but see Cappa, Niemela, & McClure Griffiths 2003).

In Rosado et al. (1996) there were some indications that bubbles around isolated main-sequence O stars are detected kinematically. In Figure 4 (from Rosado et al. 1996), Hα radial velocity profiles of the gas in the H II complex N 11B in the Large Magellanic Cloud (LMC) are displayed. The authors found signs of radial expansions (the kinematic signature of an expanding bubble) around the individual stars of the LH 10 stellar association (Lucke & Hodge 1970) that excites this nebular complex.

This search has been improved by Nazé et al. (2001) who selected LH 10 as a good candidate to search for bubbles around isolated, main-sequence O stars. Indeed, LH 10 excites N 11B which is a very dense nebular complex that surely ensures a dense medium around the massive stars of this association.

Furthermore, LH 10 contains several O3 stars, indicating that it is quite a young stellar association, where even its most massive stars have not yet exploded as supernovae, and thus no supernova remnant contamination should be found. Therefore, expanding shells in N 11B should be most likely genuine interstellar bubbles. The *HST* WFPC2 imaging did not detect any bubbles around the O stars. However, the echelle observations (described in § 3.2) indeed detected some bubbles around individual O stars. Figure 5 (from Nazé et al. 2001) gives a position-velocity diagram of one of those bubbles, clearly showing the kinematic signature of an expanding bubble. The bubbles were detected only kinematically and not morphologically because they have expansion velocities of 10 to 15 km s^{-1}, which are comparable to, or slightly larger than, the sound speed of ionized gas at 10^4 K. Consequently, the low compression factor does not allow the production of a detectable limb-brightening effect usually used to detect thin shells. The bubbles detected kinematically have, nevertheless, dynamic ages much shorter than the stellar ages (a situation that is also found in the superbubbles around the stellar associations of IC 1613, see § 6) and the stellar wind power estimated from the bubble parameters is an order of magnitude smaller than the wind power estimated from winds of stars of similar spectral types. Since the bubble expansion velocities are marginally supersonic, it is possible that in this type of conditions we need to include the ambient pressure (often neglected in the classical model predictions) in order to derive more realistic timescales and wind powers (Dopita, priv. comm.). However, the discrepancy still remains for superbubbles, where the expansion velocities are larger.

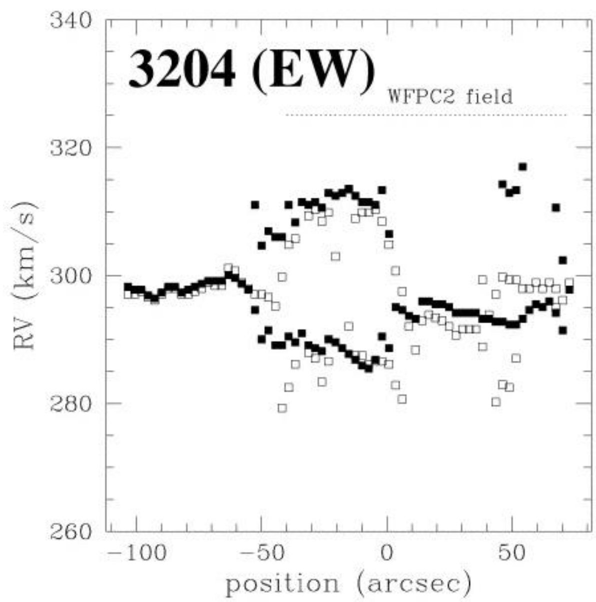

Fig. 5. Position-velocity diagram of an expanding bubble around an O star in LH 10 (from Nazé et al. 2001).

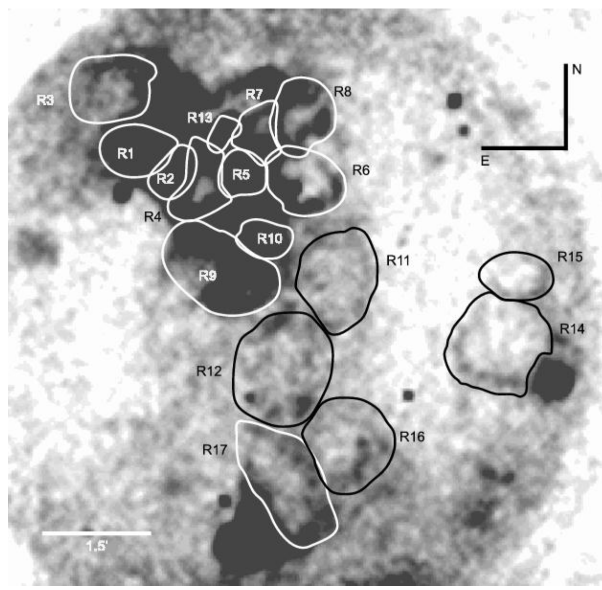

Fig. 6. Fabry-Perot velocity map (at $V_{\rm hel} = -234$ km s^{-1}) of the Hα emission of the irregular galaxy IC 1613. Superimposed on this map are the boundaries of 17 superbubbles detected in this galaxy (from Valdez-Gutiérrez et al. 2001).

6. SUPERBUBBLES IN THE IRREGULAR GALAXY IC 1613

Figure 6 shows how wind-blown bubbles can modify the ISM of an entire galaxy. Indeed, Valdez-Gutiérrez et al. (2001) have found that the ionized ISM of the irregular galaxy IC 1613 is completely pierced by several expanding superbubbles (diameters ≤ 500 pc), formed by the winds and supernova explosions of the interior stellar associations (see Lozinskaya, Moiseev, & Podorvanyuk 2003). Furthermore, young stellar associations are located at the superbubble boundaries, suggesting that shock-induced star formation is operating in this galaxy.

7. CONCLUSIONS

We have shown here, with three examples, the importance of winds in the interrelationship between gas and stars and the role that the classical model of bubble evolution has played in the interpretation of observations.

The first case exemplifies how the several phases of ejection in a low-mass star conspire to form a planetary nebula. According to the colliding winds model, bipolar PNe are formed by a first asymmetrical ejection (the torus) of the exciting star during its asymptotic giant branch (AGB) phase. Later on, the fast wind of the PN nucleus flows more easily towards the poles rather than in direction of the torus, thereby forming the lobes. However, the possibility of having three different ejections seems to better describe the observations: a spherical ejection during the AGB phase, an asymmetrical ejection of the torus during the post-AGB phase, and a current fast wind. Theoretical models therefore need to consider the interaction of three colliding winds, not two.

The second case refers to the detection of wind-blown bubbles around isolated O stars. The bubbles detected here are ISM bubbles (not circumstellar medium bubbles). Thus, the bubbles studied in Nazé et al. (2001) are the simplest systems in which to check theoretical models of bubble evolution. Several discrepancies have been found when comparing the observations with the theoretical models. It is possible that by including the initial ambient pressure some of these discrepancies may disappear.

The third case shows how the effects of massive stars (winds and supernova explosions) can shape the ISM of a whole galaxy. Also, in this case, the properties of the expanding superbubbles are not fully explained by the classical model, indicating that perhaps an important ingredient is missing.

The confrontation between theory and observations is very fruitful for the understanding of the formation and evolution of PNe and wind-driven bubbles. The discrepancies found between theory and observations can help us to get a better insight of the physical mechanisms and to search for more conclusive observational means.

The authors wish to thank the SOC and LOC of this nice meeting for the invitation. They also wish to acknowledge the financial support from grant IN104696 of DGAPA-UNAM.

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