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Review

AN OVERVIEW OF THE OBSERVATIONAL AND THEORETICAL STUDIES OF HH 1 AND 2

A. C. Raga,[1] B. Reipurth,[2] J. Cantó,[3] M. M. Sierra-Flores,[1] and M. V. Guzmán[4]

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RESUMEN

Presentamos una descripción de la bibliografía sobre los objetos HH 1 y 2, desde el descubrimiento de los objetos HH (por Herbig y Haro en 1951/2) hasta el año 2010. El trabajo sobre HH 1 y 2 traza la historia del campo de los objetos Herbig-Haro, e incluye la mayor parte de los eventos importantes en el desarrollo de nuestro entendimiento de los flujos de estrellas jóvenes.

ABSTRACT

We present a description of the bibliography of HH 1 and 2, from the discovery of HH objects (by Herbig and Haro in 1951/2) up to the year 2010. The work on HH 1 and 2 traces the history of the field of Herbig-Haro objects, and includes most of the important developments of our understanding of outflows from young stars.

Key Words: ISM: jets and outflows — ISM: kinematics and dynamics — stars: mass-loss — stars: pre-main sequence

1. INTRODUCTION

HH 1 and 2 have played a fundamental role in the development of the field of Herbig-Haro (HH) objects. They were the first HH objects that were discovered, and were the exclusive objective of all of the early studies of HH spectra. Also, many of the main properties of HH objects (for example, the proper motions, and UV, radio continuum and X-ray emission) were first seen in the HH 1/2 system. Finally, many of the theoretical ideas about HH objects were first formulated so as to explain the characteristics of HH 1 and 2.

Given this fundamental role of HH 1 and 2 in the field of HH objects, we have collected a comprehensive bibliography of the (mostly refereed) papers on the HH 1/2 system. These papers include the HH 1/2 observations at all wavelengths and the theoretical papers with models that are specifically applied to HH 1 and 2. We have proceeded to make a commented bibliography[5] describing the contributions of all of these papers.

We first give a description of the region around HH 1 and 2, discussing the general observational results (§ 2). We then describe the criteria that were used to select the papers on HH 1 and 2, and give a short description of the time distribution of the publications (§ 3). We then summarize the work that has been done regarding optical observations (§§ 4 and 5), observations in other wavelength ranges (§ 6), and theoretical models (§ 7). We then choose a set of 8 specific topics for which the HH 1/2 system has played a particularly important role, describe their development, and comment on the still unfinished work on each topic (§ 8). A short bibliographic study describing the collaborations that have dominated the research on HH 1/2 is presented in § 9. The conclusions are presented in § 10.

2. THE HH 1/2 PAPER DATABASE

We have searched on the SAO/NASA Astrophysics Data System (ADS) for papers on the objects "HH 1" or "HH 2". From the 500 papers given (until the end of 2010) by the ADS, we have chosen the

[1]Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico.

[2]Institute for Astronomy, University of Hawaii at Manoa, USA.

[3]Instituto de Astronomía, Universidad Nacional Autónoma de México, Mexico.

[4]Instituto Finlay, La Habana, Cuba.

[5]Available on-line at `http://www.nucleares.unam.mx/astroplasmas/`.

ones that do present either data or theoretical models directly relevant to the HH 1/2 outflow (which of course involves somewhat subjective decisions). We have kept all refereed papers, and included papers in conference proceedings and observatory reports only if they provided information not present in the refereed literature. Finally, we have supplemented the resulting bibliography with papers on HH 1/2 found in the reference lists of the initial selection (but which do not directly appear in the ADS search described above).

In this way, we arrive at a list of 143 papers. A "commented bibliography", in which short comments describing the contributions of each of these papers are included, is available on-line[6]. A histogram showing the yearly publication rate of papers on HH 1 and 2 is shown in Figure 1. In this figure, we see that in the 1950s and 60s one paper on HH 1/2 was published every ∼2–3 years. In the 1970s, the number of papers rose dramatically, to a rate of ∼1.5 papers per year. The 1980s and 1990s had rates of ∼5 papers per year. Finally in the past decade, the rate has gone down to 2 papers per year. It is noteworthy that for the 2005–2009 period, the average publication rate has been of only 1.2 papers per year.

Therefore, unless there is renewed interest in the HH 1/2 system in the future, the papers included in our bibliography will represent the main component of our knowledge of these objects for many years to come.

3. THE HH 1/2 SYSTEM

3.1. *Overall morphology*

In the photographic plate of the original paper of Herbig (1951), one can see 3 HH objects: HH 1, 2 and 3. Figure 2 shows a photographic plate, kindly provided by George Herbig, taken on January 20, 1947 (for details, see Reipurth & Heathcote 1997). In the image from the catalogue of Herbig (1974), HH 1, 2 and the C-S star (lying on the axis joining HH 1 and 2, about 1/4 of the way from HH 1 to 2) are seen. We note that the nature of HH 3 is unclear; Reipurth (1989) identifies HH 3 as being part of a separate outflow system to the W of HH 1/2 with an outflow axis almost parallel to the HH 1/2 axis, but more detailed proper motion studies are required to clarify whether HH 3 is a separate flow.

The first (pre-COSTAR) HST images of HH 2 were obtained by Schwartz et al. (1993). Subsequently HST has imaged both HH 1 and 2 a number of times. Figure 3 shows a pair of deep HST images

[6]`http://www.nucleares.unam.mx/astroplasmas/`.

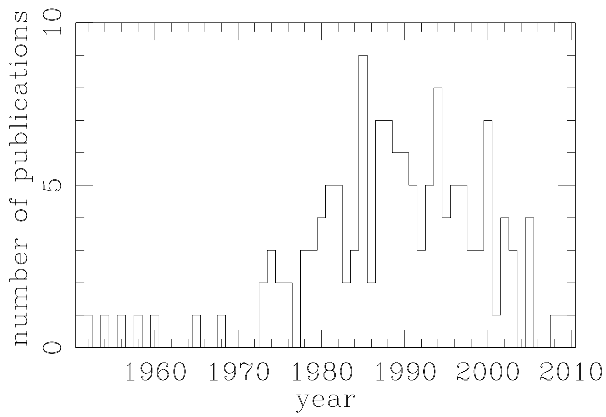

Fig. 1. Yearly number of publications on the HH 1/2 system.

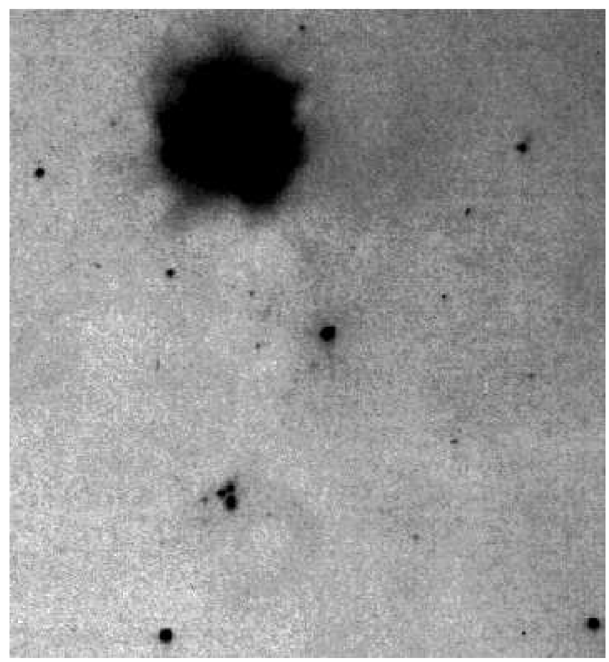

Fig. 2. HH 1, 2, and 3 as seen in an enlargement of an unpublished plate obtained by George Herbig on Jan 20, 1947. For further details, see Reipurth & Heathcote (1997).

of HH 1-2 in Hα and [SII] filters, from Bally et al. (2002). The entire bipolar outflow is almost 3 arcminutes long, corresponding to an overall projected extent of 0.35 pc at the assumed distance of ≈400 pc, which is the currently best distance estimate for the general region (see Muench et al. 2008 for a detailed discussion of the distance to the Orion Nebula Cluster region). HH 1 shows a fine bow shock structure, with an extent of ∼10 arcsec, with wings swept back-

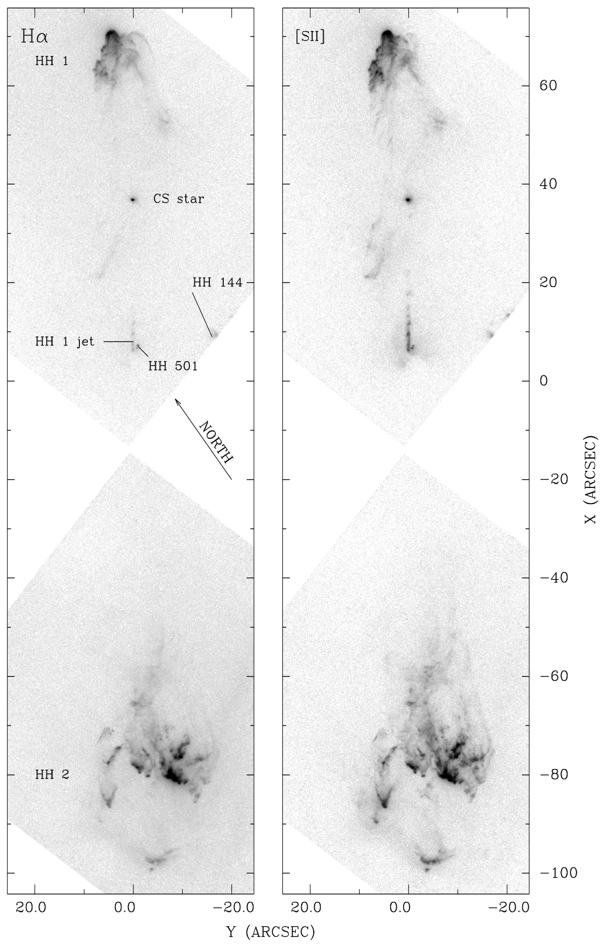

Fig. 3. Hα (left) and [S II] 6716+30 (right) HST images of HH 1 and 2. This figure is Figure 2 in the paper of Bally et al. (2002).

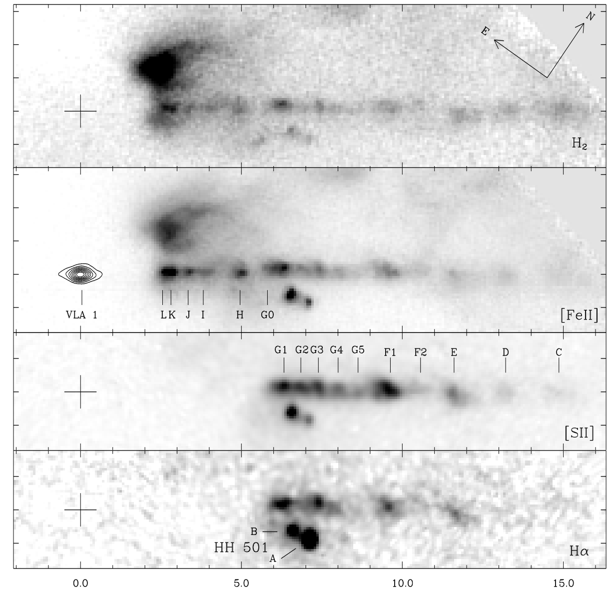

Fig. 4. The HH 1 jet in H_2 2.12 μm (top), [Fe II] 1.64 μm (second from top), [S II] 6716+30 (third) and Hα (bottom). This is Figure 1 of Reipurth et al. (2000).

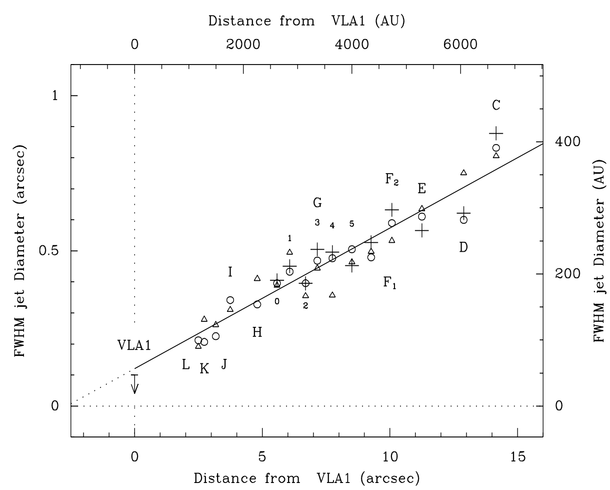

Fig. 5. Lateral expansion of the HH 1 jet. This is Figure 3 of Reipurth et al. (2000).

wards and intense emission at the apex. HH 2, on the other hand, is much larger (≈25×40 arcsec) and is fragmented into a multitude of separate bow-shaped knots and wisps of nebulosity.

Prominently visible in the center of the [SII] image is the HH 1 jet. In the plates of Herbig & Jones (1981), the jet emission can be seen. Attention was drawn to this feature when the first "electronic detector" images of HH 1 and 2 were obtained (Bohigas et al. 1985; Strom et al. 1985), and the HH 1 jet has been studied in great detail since then. Optical HST images are discussed by Hester, Stapelfeldt, & Scowen (1998) and Bally et al. (2002), and IR HST images of the jet are analyzed by Reipurth et al. (2000). Figure 4 shows the HH 1 jet at optical and infrared wavelengths. Measurements of deconvolved FWHM widths of individual knots reveal that the jet is expanding (Figure 5), and also show evidence that near the source the jet must form a wideangle wind. Nisini et al. (2005) obtained long-slit optical and infrared spectra of the HH 1 jet, and discussed the physical conditions along the jet.

Ogura (1995) presented wide field images of two large clusters of HH knots (named HH 401 and 402 for the north and south objects, respectively), with their centers at ∼25′ from the HH 1 jet and centered on the HH 1/2 outflow. These objects most likely correspond to previously ejected bow shocks; they

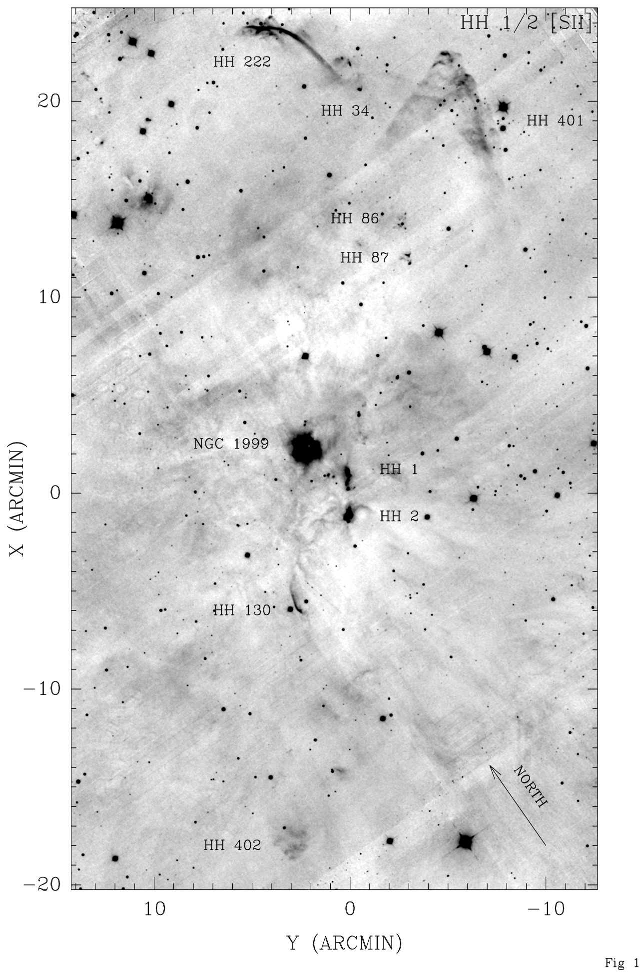

Fig. 6. Wide field [S II] 6716+30 image of the region around HH 1 and 2. This is Figure 1 of Bally et al. (2002).

are seen very clearly in Figure 6, a wide field image from Bally et al. (2002). At smaller angular scales, Reipurth et al. (1993b) reported the discovery of HH 144/145, which emanate from the source region.

As the HH 1 and 2 shocks plough through the ambient medium, they entrain and accelerate the ambient medium, and result in a bipolar molecular outflow. Despite many attempts (e.g., Chernin & Masson 1995; Correia, Griffin, & Saraceno 1997), no certain detection of this molecular counterpart to the optical HH 1/2 flow was achieved until Moro-Martín et al. (1999) obtained high angular resolution and high sensitivity ^{12}CO observations with the IRAM 30 m telescope. The difficulty in detecting this molecular outflow is likely due to the fact that HH 1 and 2 move close to the plane of the sky, as indicated by the high tangential motions and low radial velocities (Herbig & Jones 1981); an approximate angle to the plane of the sky of $\sim 10°$ was suggested by Noriega-Crespo, Böhm, & Calvet (1991).

Several HH flows in the HH 1/2 region share approximately the same outflow direction, which is perpendicular to filaments outlining the presence of tenuous molecular cloud material (Reipurth 1989). It has been speculated that global magnetic fields might be responsible for aligning the outflow activity in the region, but this has not been borne out by more detailed studies (e.g. Kwon et al. 2010).

3.2. *The source of HH 1 and 2*

In the first papers on HH 1 and 2, it was speculated that the stellar sources exciting the emission could lie within the HH objects themselves. Cohen & Schwartz (1979) later suggested that the source of HH 1 could be the C-S star, $\sim 30''$ to the SE of HH 1. The proper motions measured by Herbig & Jones (1981) suggested that both HH 1 and 2 could be the result of a bipolar ejection (the fact that HH 2 is considerably more spatially extended appeared to be consistent with the fact that it is farther away from the C-S star). Mundt & Hartmann (1983) noted that the C-S star does not seem to have a strong enough wind to be able to power HH 1 and 2 (speculating that an eruptive event might have occurred in the past). More recently, Bally et al. (2002) found the C-S star to be a close binary.

Pravdo et al. (1985) reported the radio continuum detection of HH 1 and 2, together with a source lying at mid-distance between the two HH objects. This "VLA 1" source was suggested as producing the HH 1/2 outflow. This is now accepted as being the outflow source, given the fact that a wealth of observational data supports this. Examples of this are the flattened molecular structures (perpendicular to the outflow) surrounding the VLA 1 source (see Torrelles et al. 1994, and references therein) and the resolution of VLA 1 into a radio continuum jet with travelling knots (Rodríguez et al. 2000). The radio continuum study of Rodríguez et al. (2000) also revealed a second, fainter source, VLA 2 about 3 arcsec south of VLA 1. Following the identification of a second small outflow (HH 501, Hester et al. 1998, Reipurth et al. 2000, Bally et al. 2002) emanating from the source region next to the HH 1 jet, Reipurth (2000) argued that VLA 1 must be an unresolved binary, forming a hierarchical triple system with VLA 2.

VLA 1 is a deeply embedded Class 0 source, and the cold infalling envelope around this source was detected at 1300 μm by Reipurth et al. (1993a), who estimated a mass of circumstellar material of $\sim 4\ M_\odot$.

More recently Fischer et al. (2010) used the Herschel Space Telescope to image the HH 1/2 region at far-infrared wavelengths, and in addition to the (unresolved) VLA 1/2 stellar system (their source HOPS 203), they detected another protostar, HOPS 165, only 13 arcseconds away. It thus appears that the HH 1/2 source region contains a small quadruple system of protostellar objects in very early evolutionary stages. Substantial progress in the observations of the region around VLA 1 is to be expected when this region is observed with ALMA.

4. THE DISCOVERY PAPERS

Herbig (1951) obtained spectra of HH 1 and 2, and also showed a photographic image of the region around the two objects. Herbig noted the unusual characteristics of the spectrum, which include the strength of the red [S II] lines, and the wide range of ionization+excitation energies (given by the presence of strong [O I], [O II] and [O III] lines). Herbig (1951) noted that there are no blue stars (which might photoionize the gas) visible in the region, and suggested that the excitation might be powered by accretion onto a late-type dwarf. Haro (1952) and Haro & Minkowski (1960) obtained deeper plates, and lowered the brightness for possible stars within HH 1 and 2. The name "Herbig-Haro objects" was proposed by Ambartsumian (1954).

Böhm (1956) obtained spectra of HH 1, and used diagnostic lines to determine n_e and T (the electron density and temperature) of the object. Böhm noted that the (at least partially) ionized gas cannot be in coronal ionization equilibrium at the measured temperature of ≈7500 K. Böhm (1956) commented that HH 1 is too large (with a size of ∼1000 AU) compared to the accretion radius around a low mass star (∼10 AU) for the object to be powered directly by accretion.

Osterbrock (1958) presented further spectrophotometry of HH 1, confirming the results of Böhm (1956). Osterbrock suggested that high energy particles in a stellar wind might be producing the observed ionization (without mentioning shocks). This idea was followed in more detail by Magnan & Schatzmann (1965). It is notable that these initial papers were very well directed, pointing in the general direction of later developments in the field of HH objects.

5. OPTICAL OBSERVATIONS

5.1. *Imaging*

Including the paper with the first published image of HH 1/2 (Herbig 1951), there are 19 papers with images of this outflow. Photographic plates were published by Haro (1952), Haro & Minkowski (1960), Herbig (1974), Herbig & Jones (1981, the first determination of proper motions in HH flows). Ground-based images with electronic detectors were presented by Bohigas et al. (1985), Strom et al. (1985), Raga et al. (1988), Reipurth (1989), Raga, Barnes, & Mateo (1990), Reipurth et al. (1993b), Eislöffel, Mundt, & Böhm (1994), Ogura (1995) and Warren-Smith & Scarrot (1999, presenting imaging polarimetry). Images obtained with the HST were presented by Schwartz et al. (1993), Ray et al. (1996), Hester et al. (1998), Reipurth et al. (2000) and Bally et al. (2002, who obtained proper motions from HST images).

5.2. *Spectrophotometry*

Starting with the original paper of Herbig (1951), 15 papers have been published with observations of emission line fluxes and/or the optical continuum of HH 1 and 2. The main components of this work are the calculations of n_e and T_e diagnostics and the calculations of the gas-phase abundances.

The first of these studies was published by Böhm (1956), who presented diagnostic line ratios and discussed the possible reddening corrections. This work was later extended with detections of progressively more lines by Böhm, Perry, & Schwartz (1973: 60 lines), Böhm, Siegmund, & Schwartz (1976: reddening from the IR and blue [S II] lines), Schwartz (1976), Dopita (1978), Böhm & Brugel (1979), Brugel, Böhm, & Mannery (1981a), Strom et al. (1985) and Solf, Böhm, & Raga (1988: 175 lines in HH 1). Cohen & Schwartz (1979) and Mundt & Hartmann (1983) presented the spectrum of the "Cohen-Schwartz" (C-S) star, which was suggested as a possible source of the HH 1/2 system (later demoted, see § 3.2). The optical continuum emission of HH 1 and 2 was studied by Böhm, Schwartz, & Siegmund (1974), Brugel, Böhm, & Mannery (1981b) and Solf et al. (1988).

5.3. *High resolution spectroscopy*

There are 12 papers discussing line profiles of the emission of the HH 1/2 region. The first mention of the line profiles of HH 1/2 was that of Böhm et al. (1973), who stated that the line widths are ∼1 Å. Radial velocities and line widths were studied by Schwartz (1978, 1981) and Dopita (1978). Hartmann & Raymond (1984) and Böhm & Solf (1985) and Hartigan, Raymond, & Hartmann (1987) presented the details of short- and long-slit line profiles of HH 1 and 2. The two-dimensional spatial distributions of the line profiles of HH 1 (Solf et al. 1991) and

HH 2 (Böhm & Solf 1992) have also been described. Solf & Böhm (1991) discussed the line profiles of the diffuse emission around HH 1 and 2 (possibly due to scattering on surrounding environmental dust). This effect was also studied by Riera et al. (2005), who presented Fabry-Perot observations of HH 1 and 2.

6. OTHER WAVELENGTH RANGES

6.1. *UV observations*

The far-UV emission of HH 1 was discovered with IUE by Ortolani & D'Odorico (1980). A series of papers described IUE observations of the emission line and continuous UV spectrum of HH 1 (Böhm, Böhm-Vitense, & Brugel 1981), HH 2 (Brugel, Seab, & Shull 1982) and the C-S star (Böhm & Böhm-Vitense 1982). The spatial extent of the UV emission was studied by Böhm-Vitense et al. (1982), Böhm et al. (1987), Lee et al. (1988) and Böhm, Noriega-Crespo, & Solf (1993). The UV variability of HH 1 was discussed by Brugel et al. (1985) and Böhm et al. (1993). The UV extinction was studied by Böhm-Vitense et al. (1982) and Böhm, Raga, & Binette (1991).

The most recent UV observations of HH 2 were obtained by Raymond, Blair, & Long (1997) with the Hopkins Ultraviolet Telescope. In this spectrum, lines of several ions (e.g., O III and IV) as well as H_2 lines were identified.

6.2. *IR observations*

Including the discovery paper of IR H_2 emission in HH 1 and 2 (Elias 1980), 25 papers on the IR spectra of these objects have been published. These papers include searches of potential sources for the HH 1/2 system (Cohen & Schwartz 1980; Cohen et al. 1984) and of the later accepted VLA 1 source (Strom et al. 1985; Rodríguez, Roth, & Tapia 1985; Harvey et al. 1986; Pravdo & Chester 1987; Tapia et al. 1987; Roth et al. 1989). Cernicharo et al. (2000) presented ISO observations of the VLA 1 region. Low and high resolution spectra of the H_2 emission of HH 1 and 2 were presented by Zinnecker et al. (1989), Kelly, Rieke, & Campbell (1994), Schwartz et al. (1995), Gredel (1996), Davis, Smith, & Eislöffel (2000), Eislöffel, Smith, & Davis (2000), Nisini et al. (2005) and García López et al. (2008), the last three papers presenting long-slit spectra. Molinari & Noriega-Crespo (2002), Lefloch et al. (2003) and Lefloch et al. (2005) obtained ISO spectra of HH 1 and 2.

H_2 2.12 μm images of HH 1 and 2 have been presented by Zealey et al. (1992), Noriega-Crespo & Garnavich (1994), Davis, Eislöffel, & Ray (1994), Noriega-Crespo et al. (1997, discovery of H_2 proper motions in HH objects), Davis et al. (2000) and Stanke, McCaughrean, & Zinnecker (2000).

6.3. *Radio observations*

The first paper (out of a total of 19 papers) on radio observations of HH 1/2 (Snell & Edwards 1982) reported the non-detection of a CO outfow. HH 1 and 2 as well as the central VLA 1 source (the source that powers the HH 1/2 system) were first detected in radio continuum by Pravdo et al. (1985) at 20, 6 and 2 cm (HH 1 was actually not detected at the shorter wavelength). Morgan, Snell, & Strom (1990) reported a detection at 6 cm and a non-detection at 20 cm of the radio continuum of HH 1/2 and VLA 1. Rodríguez et al. (1990) detected the radio continuum proper motions of HH 1 and 2, and Rodríguez et al. (2000) obtained proper motions of knots within the elongated VLA 1 source.

Different molecules were detected in dense structures centered on VLA 1 and elongated perpendicularly to the outflow axis (Torrelles et al. 1985; Martín-Pintado & Cernicharo 1987; Marcaide et al. 1988; Davis et al. 1990; Torrelles et al. 1993, 1994; Choi & Lee 1998). Molecular emission associated with clumps which are perturbed (possibly only radiatively) by HH 1 or HH 2 have been studied by Davis et al. (1990), Torrelles et al. (1992, 1993), Choi & Zhou (1997), Girart et al. (2002, 2005) and Dent, Furuya, & Davis (2003).

6.4. *X-ray observations*

Pravdo & Angelini (1993) report ROSAT observations of a region containing HH 1/2, and specifically mention the non-detection of HH 1 (giving an upper limit for its flux). A paper on the X-ray emission of HH 2 (Pravdo et al. 2001) reports the discovery of the X-ray emission of HH objects. The spectrum observed with Chandra implies the presence of gas at $\sim 10^6$ K.

7. MODELS OF HH 1/2

The idea of HH objects being the result of shock waves was first suggested by Schwartz (1975), who noticed similarities between the spectra of supernovae remnants and the spectra of HH 1 and Burnham's nebula. Böhm (1978) proposed that HH 1 might be the result of a spherically expanding shock wave, and Schwartz (1978) proposed that HH 1 and 2 might be bow shocks formed by a fast wind interacting with almost stationary, dense clumps. Cantó & Rodríguez (1980) proposed that the HH 1 shock waves were associated with the convergence region of a nozzle flow. These three scenarios turned out to be not applicable to HH 1 and 2.

Two other scenarios were proposed for producing HH bow shocks: the "interstellar bullet" model of Norman & Silk (1979, who do not explicitly mention HH 1 and 2) and the "jet" model of Dopita, Schwartz, & Evans (1982b, suggested for HH 46/47). Interestingly, these two scenarios were favored (over the "shocked cloudlet" and "nozzle" models) by the high HH 1/2 proper motions discovered by Herbig & Jones (1981).

Predictions of emission line ratios from stationary, plane-parallel shocks were compared with observations of HH 1/2 by Dopita (1978) and Raymond (1979). The production of the optical continuum in plane-parallel shock waves was discussed by Dopita, Binette, & Schwartz (1982a) and predictions of the radio continuum were made by Curiel, Cantó, & Rodríguez 1987). The H_2 emission of HH 1 was modeled by Wolfire & Königl (1991).

The first "3/2-D" bow shock models (constructed with 1D shocks distributed over a given bow shock shape) were applied to HH 1 and 2 by Hartmann & Raymond (1984). Predictions of line profiles, PV diagrams, line ratios and the spatially resolved line emission from such models were applied to HH 1 and 2 by Choe & Böhm (1985), Raga & Böhm (1985), Hartigan et al. (1987), Raymond, Hartmann, & Hartigan (1988), Noriega-Crespo, Böhm, & Raga (1989, 1990), Indebetouw & Noriega-Crespo (1995), Moro-Martín et al. (1996), Henney (1996, non-axisymmetric bow shocks) and Raga et al. (1997, proper motions in 3/2-D bow shocks).

Axisymmetric, time-dependent bow shock simulations were presented by Raga & Böhm (1987) and Raga et al. (1988), who modeled the proper motions and line profiles of HH 1. A two-plane shock model for the working surface of a jet was described by Hartigan (1989), and axisymmetric simulations of the head of a jet (with predictions of intensity maps for comparisons with HH 1) were presented by Raga (1988), and Blondin, Königl, & Fryxell (1989), Blondin, Fryxell, & Königl (1990). 3D jet head simulations were presented by de Gouveia Dal Pino & Benz (1993) and Stone & Norman (1994, for HH 2). Predictions of the H_2 emission of HH 1 from a jet head simulation were made by Raga et al. (1995), and of the X-ray emission of HH 2 by Raga, Noriega-Crespo, & Velázquez (2002). A precessing jet model was suggested for HH 1 and 2 by Lightfoot & Glencross (1986, most likely incorrect, but being the first suggestion of the importance of precession in HH jets).

Models for scattering of the HH 1 emission in the surrounding, dusty environment were described by Noriega-Crespo et al. (1991) and Henney, Raga, & Axon (1994) and for HH 2 by Riera et al. (2005). The photochemistry of environmental clumps irradiated by HH 1/2 was modeled by Raga & Williams (2000) and Viti et al. (2003).

8. SPECIAL TOPICS

8.1. *Proper motions*

One of the main discoveries made in observations of HH 1 and 2 was the large proper motions of HH objects. Herbig & Jones (1981) measured large proper motions (mostly in the 100–300 km s^{-1} range) for the HH 1 and 2 condensations. These proper motions appear to indicate that the two objects were ejected from a common source, and eliminated stationary flow models for HH 1 and 2 (Cantó & Rodríguez 1980), as well as the "shocked cloudlet" model (Schwartz 1978). Gyul'budagyan (1984) noted that these proper motions indicated a divergence beyond what could be expected from ballistic trajectories from the outflow source (at that time assumed to be the C-S star, though the same argument applies for the VLA 1 source).

This divergence phenomenon was successfully explained in terms of bow shock models. Raga & Böhm (1987) and later Raga et al. (1997) showed numerically and analytically that knots at the head of a bow shock have purely forward motions, and knots associated with the far bow shock wings have mostly lateral motions, therefore producing an "expansion pattern" similar to the one observed in HH 1 and 2.

The proper motions of the HH 1/2 system were later measured in radio continuum maps (Rodríguez et al. 1990, 2000) and in IR H_2 images (Noriega-Crespo et al. 1997). Also, the proper motions of the optical knots were progressively improved and extended (to more knots) by Eislöffel et al. (1994) and by Bally et al. (2002, using HST images).

One should note that HST images allow measurements of proper motions with epochs spaced at intervals of only a few years. Therefore, further HST images of the HH 1/2 system (only two epochs were used by Bally et al. 2002) would provide the possibility of seeing the time-evolution of the proper motions of the line emitting knots. If such a time-evolution were detected, it would again be the first time that HH 1 and 2 show interesting properties possibly shared by HH objects in general.

8.2. *Dispersion of HH emission on dust*

Strom, Strom, & Kinman (1974) measured basically zero polarization in HH 1 and 2. Interestingly, they interpreted this as evidence of the presence of multiple scattering (on dust), which could lower the polarization associated with the scattering process. This interpretation was introduced to save the idea (being forwarded at the time) of HH objects as dense clouds which reflected the light of (directly unobservable) young stars. Schmidt & Vrba (1975) lowered the limit of the (undetected) polarization of HH 1 and 2 to a fraction of 1%, and (correctly) concluded that the emission from HH 1 and 2 had to be intrinsic. The paper of Mundt & Witt (1983) explored the possibility that the UV continuum of HH 1 and 2 might be contaminated by a reflected, blue star continuum (a suggestion that was later put aside).

Interestingly, the problem of scattering on dust gained new life with the paper of Solf & Böhm (1991), who detected the presence of faint but very broad line profiles off the bright knots of HH 1. They interpreted this as evidence of scattering on environmental dust of the emission spectrum of the HH 1 knots. This idea was explored theoretically by Noriega-Crespo et al. (1991), Henney et al. (1994) and Riera et al. (2005).

Warren-Smith & Scarrot (1999) carried out continuum and Hα imaging polarimetry of the HH 1/2 system, finding polarizations of a few percent in the Hα emission at some positions around HH 1. No comparison has been made with the polarization predictions of Henney et al. (1994). There is clearly room for more work on this topic.

8.3. *The emission line spectrum*

The emission line spectrum (UV, optical, IR and radio) of HH 1 and 2 provides most of the information known about these objects. The best data currently available on the optical emission line ratios of HH 1 were obtained by Solf et al. (1988, who identified 175 lines). The best IR spectrophotometry was carried out by Gredel (1996) and by Molinari & Noriega-Crespo (2002, ISO spectra), and the best UV data were obtained by Böhm et al. (1993, IUE data) and by Raymond et al. (1997, HUT data).

The emission line ratios observed in HH 1 and 2 have motivated the shock interpretation of HH objects (Schwartz 1975). The spectra of HH 1/2 were first compared with predictions of plane-parallel shock models (Dopita 1978; Raymond 1979). The spectrophotometric observations of Brugel et al. (1981a) later showed that the emission of HH 1/2 (and a set of other HH objects) has low filling factors of $\sim 10^{-3} \rightarrow 10^{-2}$ (depending on the emission line), which is one of the main qualitative observational features expected for shock emission.

Later, comparisons with "3/2-D" bow shock models (built as an appropriate superposition of 1D shocks) were done by Hartmann & Raymond (1984) and Hartigan et al. (1987). The last two papers showed that the combination of (normal) shock velocities produced by a continuous bow shock resulted in line ratios that better reproduced the HH 1 and 2 spectra. Predictions of the spatially resolved line emission were later carried out by Noriega-Crespo et al. (1989, 1990).

The main success of the 3/2-D shock models was to reproduce some of the characteristics of the emission line profiles and/or PV diagrams of HH 1 and 2. Raga & Böhm (1985) presented 3/2-D bow shock models that reproduced the general characteristics of the PV diagrams of HH 1 obtained by Böhm & Solf (1985). In an earlier paper, Choe & Böhm (1985) had obtained predicted PV diagrams that actually agreed better with the HH 1 observations, but these models did not have a proper calculation of the line profiles from the bow shock.

Hartigan et al. (1987) modeled the line profiles of HH 1 and 2 (not PV diagrams), assuming that each condensation is a separate bow shock. This was an important difference from the models of Raga & Böhm (1985), in which all of HH 1 was modeled as a single bow shock. Later, higher angular resolution observations of HH 1 and 2 (e.g., Hester et al. 1998) showed that the condensations of HH 1 (some of them shaped as small, bow shaped shocks) do indeed seem to form a single, broken up bow shock, while the condensations of HH 2 do not form a discernible, organized larger scale structure.

While some effort has been done in modelling HH 1 (Raga 1988; Blondin et al. 1989; Völker et al. 1999) and HH 2 (Stone & Norman 1994) with full (axisymmetric or 3D) jet simulations, more work in this direction should clearly be made. For example, it would be important to carry out high resolution 3D simulations of both HH 1 and 2 to see whether or not predictions from the models are successful at reproducing the 2D distributions of emission line ratios and profiles (Solf et al. 1991; Böhm & Solf 1992) and proper motions (Bally et al. 2002). At the same time, these models should reproduce the spatially resolved line emission and line profiles of the HH 1 jet (Nisini et al. 2005; García López et al. 2008).

Such simulations should settle the doubts that still remain as to whether or not the line ratios, line profiles and proper motions observed in HH 1 and 2 can indeed be reproduced by a single model. Furthermore, this model should also be able to reproduce the observed X-ray emission of HH 2 (Pravdo et al. 2001), and the H_2 (Noriega-Crespo et al. 1997) and CO (Moro-Martín et al. 1999) emission of the HH 1/2 system. Clearly, a lot of effort will have to be done for such modelling to be successful, and non-trivial problems might be encountered.

Finally, it is notable that most of the best available observations of HH 1 and 2 have been obtained more than a decade ago. Clearly, new spectrophotometric and high dispersion spectroscopic observations would be worthwhile, as they would provide data of considerably improved quality.

8.4. *The continuum emission*

The optical and UV continua of HH 1 and 2 apparently have strong contributions from collisionally enhanced 2-photon H emission (Brugel et al. 1982; Dopita et al. 1982a). At UV wavelengths, there might also be a contribution from the H_2 dissociation continuum (Böhm et al. 1987; Lee et al. 1988).

Very little theoretical work has been done regarding the continuum emission of HH 1 and 2, and basically no effort has been done to model the spatial distribution of the continuum emission (e.g., the radio continuum predictions of Curiel et al. 1987 and Ghavamian & Hartigan 1998 were restricted to p-p shocks). Clearly, more observational and theoretical efforts will be necessary in order to contribute to the understanding of the continuum emission of HH 1/2 (and of HH objects in general).

8.5. *Abundances*

An interesting line of research has been the determination of the gas phase abundances of the HH 1/2 system. Böhm et al. (1976) found that HH 1 and 2 had abundances consistent with Population I abundances, indicating that no depletion due to dust grains was present. This result was strengthened with further data by Böhm & Brugel (1979) and Brugel et al. (1981a). Beck-Winchatz, Böhm, & Noriega-Crespo (1994) presented a re-analysis of older data, confirming the absence of dust in HH 1 (but found evidence of dust depletion in Burnham's nebula).

The paper of Nisini et al. (2005, who present 0.6–2.5 μm long-slit spectra) somewhat surprisingly find that the spectrum of the HH 1 jet (to the NW of the VLA 1 source) does show evidence for Fe, C, Ca and Ni depletions. This result implies that the gas along the jet flow does have dust.

This is a problem that merits further study. More spatially-resolved abundance determinations would be useful, as well as theoretical models of dust destruction in the shocks associated with the jet knots and jet head.

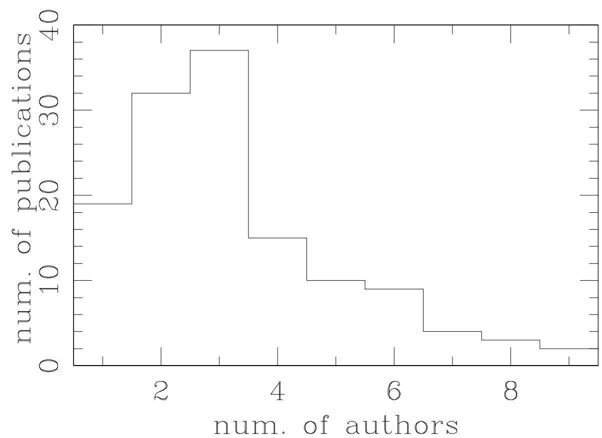

Fig. 7. Frequency distribution of the number of co-authors in the papers of the HH 1/2 database.

8.6. *Time-variability*

Herbig (1968, 1973) showed that the optical emission of both HH 1 and 2 is variable. This time-dependence was followed at later times by Herbig & Jones (1981) and Raga et al. (1990). Böhm et al. (1976) found that n_e and T_e determined from diagnostic lines also appeared to change over periods of $\sim$15 yr (in HH 1/2). Brugel et al. (1985) and Böhm et al. (1993) found that the UV spectrum of HH 1/2 showed substantial changes over periods of a few years.

Apparently, there are no more recent discussions of the variability of HH 1 and 2. What has happened during the last $\sim$10 years? Have the brightening trends (Herbig & Jones 1981) of some of the HH 2 condensations continued? Clearly, it would be worthwhile to have more up-to-date studies of this time-evolution.

9. CONTRIBUTIONS OF INDIVIDUAL AUTHORS AND COLLABORATIONS

The papers on HH 1/2 have had relatively small numbers of co-authors. Figure 7 shows the frequency distribution of the number of co-authors, with a clear peak at three co-authors, and an extended wing, ending with two papers with nine co-authors. The mean is of 3.27 authors per paper.

In order to evaluate the contribution of individual authors, we have calculated their "normalized contribution" as $c_a = \sum_i (n_{a,i})^{-1}$, where $n_{a,i}$ are the number of coauthors of the papers which include author a. We first make a list of authors in order of decreasing c_a contributions, and we then compute a cumulative distribution function.

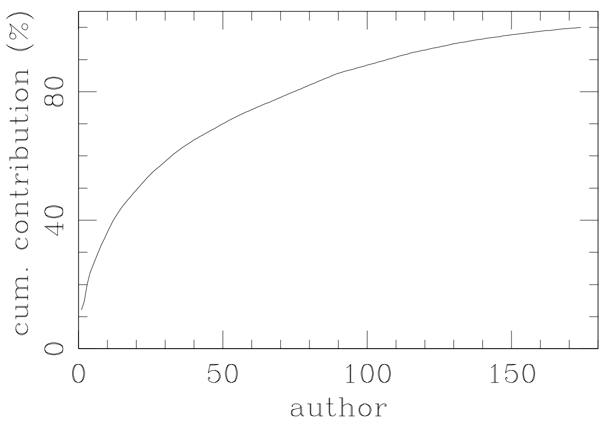

Fig. 8. Cumulative distribution of the contributions of authors to the publications of HH 1/2.

This cumulative distribution is shown in Figure 8. We find that the first author (author 1, who has the largest c_a value, see above) has a contribution of ≈12% of the total (normalized) publications on HH 1/2. From Figure 8 we see that 21 authors have contributed ≈50% of the total publications, and 107 authors have contributed ≈90%. These numbers represent the characteristic size of the group of authors who have worked on HH 1 and 2.

We have selected a "high production" set, composed of the 20 authors that have collaborated in at least 5 of the papers in our HH 1/2 database (see § 2). We have ordered this set of authors in such a way that close collaborators occupy neighbouring positions along the list. Figure 9 shows this list of authors, together with a "collaboration matrix". The diagonal elements ($C_{i,i}$) of this matrix correspond to the number of papers co-authored by each of the authors in the list. The non-diagonal elements ($C_{i,j}$; $i \neq j$) give the number of papers in which both the authors i and j appear in the list of co-authors.

In Figure 9, we note the presence of 4 groups of collaborators:

Group 1: there is a remarkably unified group of 5 collaborators (Rodríguez, Cantó, Torrelles, Ho and Curiel) in the upper right hand corner of the matrix. As can be seen from the references, this group has concentrated on line and continuum radio observations as well as models of the HH 1/2 system. It is clear that each of these authors has collaborated with all of the other four members of the group,

Groups 2 and 3: two small groups of three authors (Group 2 being composed by Raymond, Hartigan and Hartmann, and Group 3 by Eislöffel, Ray and Davis) are also evident. The papers of these two groups cover optical and IR observations. The papers of Group 2 also cover models of HH 1/2,

Group 4: the first 8 authors in our list (on the bottom, left-hand corner of Figure 9) also form a collaboration group. This group has a "core" of three authors (Böhm, Raga and Noriega-Crespo), who appear together in many papers. There is also a "secondary group" of 5 authors (Schwartz, Brugel, Solf, Reipurth and Mundt) who have collaborated with one or more of the members of the "core group" (see above), but not with all of the other members of the "secondary group". If one peruses the list of references, one sees that this group encompasses collaborations that have occurred over 5 decades, most of which are characterized by the unifying participation of K. H. Böhm. The papers of this group cover optical/IR/UV observations and models of HH 1/2.

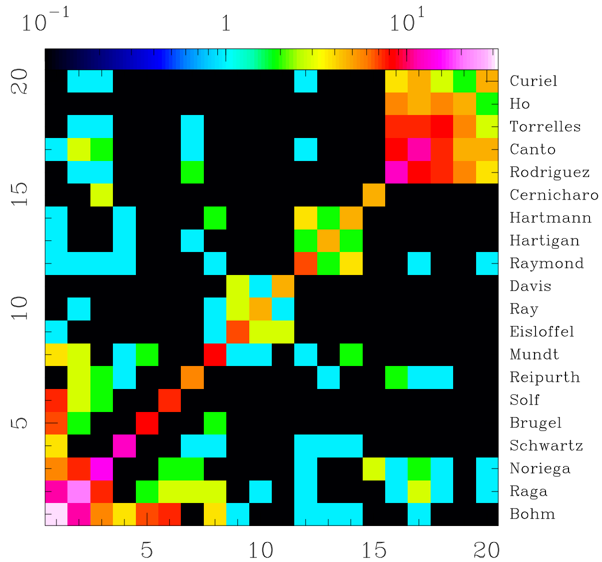

Fig. 9. Collaboration matrix. The diagonal elements give the papers including each of the authors, and the non-diagonal elements give the papers in which pairs of authors have collaborated. The order numbers correspond to the authors listed on the right of the plot. The color figure can be viewed online.

It is also clear from Figure 9 that occasional collaborations have also occurred between the members of the four groups, evidenced by the presence of nonzero elements far away from the main diagonal of the collaboration matrix.

We end this discussion of the groups of collaborators by noting again that our analysis is restricted to the researchers who are co-authors in at least 5 of the HH 1/2 papers. Individual authors (collaborating with the more active researchers) or even independent research groups with lower levels of activity in this field do not appear in our analysis.

10. SUMMARY

We have collected all the papers through 2010 that have made a substantial contribution to the study of the Herbig-Haro objects HH 1 and 2, and made a commented bibliography[7] with short comments on all papers. This excercise is meant to serve as a guide to researchers who plan future work on these objects.

The choice of the papers in this bibliography is of course somewhat subjective, because some important papers might have been missed, and also because many papers (treating, e.g., many objects or theoretical models) have only passing references to HH 1 and 2 and have therefore not been included. Nevertherless, the vast majority of papers with substantial contributions to the understanding of HH 1 and 2 are probably included in our bibliography. Furthermore, given the fact that the yearly number of publications has fallen over the past decade (see § 2), the papers in our bibliography are likely to represent the larger part of the work that will be done on these objects (unless there is renewed future interest in HH 1 and 2).

However, it is clear that research on HH 1 and 2 is still alive. Evidence of this is the paper by Hartigan et al. (2011), which presents new HST images of HH 1 and 2, leading to new results on the proper motions and variability of these objects.

In the present paper we carry out a description of the HH 1/2 system (§ 3), a discussion of the early papers (§ 4), of the observations (§§ 5 and 6), and models (§ 7) of this system. We then discuss a few special topics regarding HH objects in general, which have shown considerable progress or have been resolved through studies of HH 1 and 2 (§ 8). This discussion has references to most of the papers in our HH 1/2 bibliography.

Finally, we make a short study of the contributions of individual authors and research groups to the HH 1/2 bibliography (§ 9). From this study, it is evident that Karl-Heinz Böhm has been the driving force for a substantial part of the work done on HH 1/2 (on optical/UV observations and theoretical models), as well as Luis Felipe Rodríguez (radio observations). Most of the work that has been done on HH 1/2 involves collaborations which include one of these two authors.

[7] Available on-line at `http://www.nucleares.unam.mx/astroplasmas/`.

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J. Cantó: Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 70-264, 04510 México, D. F., Mexico.
M. V. Guzmán: Instituto Finlay, P. O. Box 16017, Cod. 11600, La Habana, Cuba (mvguzman@finlay.edu.cu).
A. C. Raga and M. M. Sierra-Flores: Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Apdo. Postal 70-543, 04510, México, D. F., Mexico (raga, sierra@nucleares.unam.mx).
B. Reipurth: Institute for Astronony, University of Hawaii at Manoa, 640 N. Aohoku Place, Hilo, HI 96720, USA (reipurth@ifA.Hawaii.Edu).