

HIGH-RESOLUTION IMAGING OF NGC 2346 WITH GSAOI/GeMS: DISENTANGLING THE PLANETARY NEBULA MOLECULAR STRUCTURE TO UNDERSTAND ITS ORIGIN AND EVOLUTION

ARTURO MANCHADO^{1,2,3}, LETIZIA STANGHELLINI⁴, EVA VILLAVER⁵, GUILLERMO GARCÍA-SEGURA⁶, RICHARD A. SHAW⁴, AND D. A. GARCÍA-HERNÁNDEZ^{1,2}

¹ Instituto de Astrofísica de Canarias, Vía Láctea S/N, E-38205 La Laguna, Tenerife, Spain

² Departamento de Astrofísica, Universidad de La Laguna (ULL), E-38206 La Laguna, Tenerife, Spain

³ Consejo Superior de Investigaciones Científicas, Spain; amt@iac.es

⁴ National Optical Astronomy Observatory, 950 N. Cherry Avenue, Tucson, AZ 85719, USA

⁵ Departamento de Física Teórica, Universidad Autónoma de Madrid, Cantoblanco E-28049, Madrid, Spain; eva.villaver@uam.es

⁶ Instituto de Astronomía-UNAM, Apartado postal 877, Ensenada, 22800 Baja California, México; ggs@astro.unam.mx

Received 2014 November 18; accepted 2015 June 9; published 2015 July 27

ABSTRACT

We present high spatial resolution (≈ 60 – 90 mas) images of the molecular hydrogen emission in the planetary nebula (PN) NGC 2346. The data were acquired during the system verification of the Gemini Multi-conjugate Adaptive Optics System + Gemini South Adaptive Optics Imager. At the distance of NGC 2346, 700 pc, the physical resolution corresponds to ≈ 56 AU, which is slightly higher than an $[\text{N II}]$ image of NGC 2346 that was obtained with the *Hubble Space Telescope*/WFPC2. With this unprecedented resolution, for the first time we were able to study the structure of the H_2 gas within the nebula in detail. We found it to be composed of knots and filaments, which at a lower resolution had appeared to be a uniform torus of material. We explain how the formation of the clumps and filaments in this PN are consistent with a mechanism in which a central hot bubble of nebular gas surrounding the central star has been depressurized, and the thermal pressure of the photoionized region drives the fragmentation of the swept-up shell.

Key words: hydrodynamics – ISM: jets and outflows – planetary nebulae: general – planetary nebulae: individual (NGC 2346) – stars: winds, outflows

1. INTRODUCTION

Molecular hydrogen (H_2) was first detected in the Galactic planetary nebula (PN) NGC 2346 by Zuckerman & Gatley (1988). Thanks in part to its proximity, several authors have studied its H_2 gas emission in detail since then (e.g., Kastner et al. 1994, 1996; Latter et al. 1995; Vicini et al. 1999; Arias et al. 2001). They described an apparent structure of clumps and a torus not uncommon in PNs. Neutral clumps have been detected in PNs in nearby extended objects such as NGC 6543 or NGC 6852 (Meaburn & López 1993) and cometary knots seem to often be detected in evolved PNs if the resolution allows it (e.g., Huggins et al. 2002; O’Dell et al. 2002). However, the formation of these small-scale structures is not well understood and different mechanisms have been proposed to explain their formation. Some involve the formation of clumps prior to photoionization (Soker 1998), while others have suggested that preexisting high-density structures in the interstellar medium (ISM) are responsible for the structures observed later on that are embedded in the PN shell (Alūzas et al. 2012). The hydrodynamical evolution of those clumps has been studied by Redman et al. (2003) and Alūzas et al. (2012) and other mechanisms such as their formation in the progenitor asymptotic giant branch (AGB) atmosphere have been ruled out (Huggins & Mauron 2002). García-Segura et al. (2006) proposed that clumps are the result of the fragmentation of the swept-up shell.

The central star of NGC 2346 is in a close binary system (Méndez & Niemela 1981, hereafter MN81), with a measured period of ≈ 16 days. Given its small orbital separation, it is possible that the system is the remnant of common-envelope (CE) evolution. However, alternative scenarios for its formation have also been proposed. Davis et al. (2010), and de Kool

& Ritter (1993) have suggested that the system did not evolve through CE; rather, it went through mass transfer from an evolved primary with a radiative envelope into the companion, via a thermally unstable Roche Lobe overflow.

The role of binaries in the evolution from the AGB to the PN phase is not well understood. This is mainly because only 40 binary central-stars of PNs have been studied (De Marco et al. 2013). From these only a small fraction are believed to have undergone CE evolution (e.g., Miszalski et al. 2013; Corradi et al. 2014). In the CE phase the ejection of the envelope is closely confined to the equator (e.g., Sandquist et al. 1998, Ricker & Taam 2012); Ricker & Taam (2012) found that 90% of the outflowing material is confined to an angle of 30° on either side of the equatorial plane.

In this paper we study in detail the structure and gas distribution of H_2 in NGC 2346 using exquisite, high-resolution images from observations with the Gemini Multi-conjugate Adaptive Optics System (GeMS) + Gemini South Adaptive Optics Imager (GSAOI). We also study the properties of the binary central star system. In Section 2 we describe the observations; Section 3 includes a description of the molecular hydrogen emission; in Section 4 we discuss the stellar progenitor mass; Section 5 gives a general discussion of the results; finally, we summarize our findings and conclusions in Section 6.

2. OBSERVATIONS

We used the GeMS + GSAOI during system verification (2013 March). GeMS (Rigaut et al. 2014, Neichel et al. 2014) comprises multiple deformable mirrors and uses three natural guide stars and five sodium laser guide stars. GSAOI is a near-infrared camera used with GeMS on Gemini South (McGregor

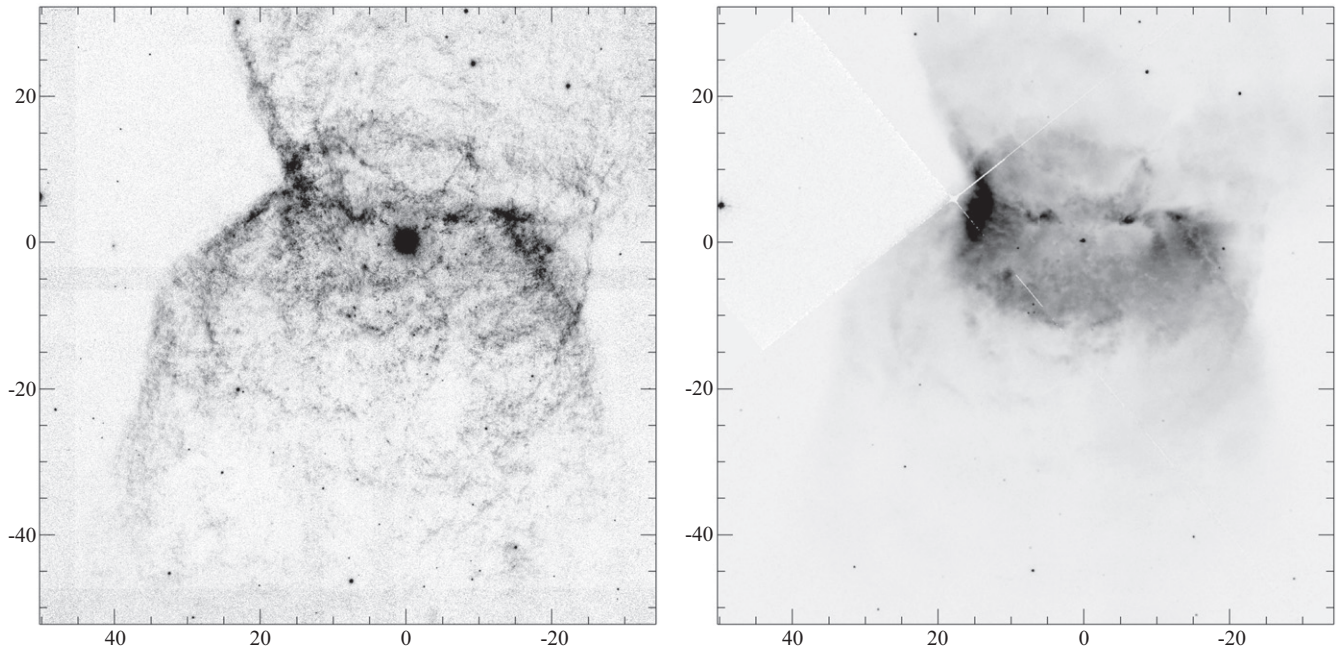


Figure 1. Images of NGC 2346 obtained with GSAOI in H_2 (1-0) S(1) (left panel), and with *HST*/WFPC2 in [N II] (right panel). Images are oriented with north up and east to the left; tick labels are in arcseconds with respect to the central star.

et al. 2004, Carrasco et al. 2012). GSAOI provides diffraction-limited images in the $0.9\text{--}2.4\ \mu\text{m}$ range, using a 2×2 mosaic Rockwell HAWAII-2RG 2048×2048 array. The GSAOI field of view (FOV) is $85'' \times 85''$ with a scale of $0''.02\ \text{pixel}^{-1}$ and a gap between the arrays of $\approx 2\ \text{mm}$ (which corresponds to $2''.2$ on the sky).

We obtained narrow-band images in the H_2 (1-0) S(1) $2.122\ \mu\text{m}$, Br γ $2.166\ \mu\text{m}$, and H_2 (2-1) S(1) $2.248\ \mu\text{m}$ filters with good natural seeing conditions ($0''.4\text{--}0''.5$). We used five dither positions with individual exposure times of 120 s for the H_2 (1-0) S(1) images and 360 s for the Br γ and H_2 (2-1) S(1) images. As the object is larger than the FOV, adjacent sky frames were taken with the same exposure time. Exposure time, which was on-target, was 600 s for the H_2 (1-0) S(1) image and 1800 s for the Br γ and H_2 (2-1) S(1) images. Data reduction, including distortion correction, was carried out using the Gemini IRAF⁷ package v1.12, *gsaoi*. After the combination of all the images for each band we found that the FWHM varies over the whole FOV, between 60 and 90 mas, with an average value of 80 mas. We used 2MASS K_s band magnitudes of several field stars to flux calibrate the H_2 (1-0) S(1) images. Transmission of the H_2 (1-0) S(1) $2.122\ \mu\text{m}$ filter is about 90% and the width is $0.032\ \mu\text{m}$. A color correction between the center of the K_s band ($2.159\ \mu\text{m}$) and the center of the H_2 (1-0) S(1) line ($2.122\ \mu\text{m}$) was applied, which led to an uncertainty of 1% in the flux calibration. The statistical error in the flux calibration, as measured from different field stars, is about 2%. Thus, altogether the error in the flux calibration is approximately 2.2%. We obtained an inverse sensitivity for point sources of $4.94 \pm 0.10 \times 10^{-18}\ \text{erg}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}$ per electron. The pixel area is $9.5 \times 10^{-15}\ \text{sr}$, so the inverse sensitivity for

extended sources is $5.25 \pm 0.10 \times 10^{-4}\ \text{erg}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$ per electron.

Figure 1 shows the resulting image of the H_2 (1-0) S(1) $2.122\ \mu\text{m}$ emission. The signal-to-noise ratio of the extended emission in the Br γ and the H_2 (2-1) S(1) images is less than 2σ and they are not shown in the paper. The [N II] image was obtained with the WFPC2 on board the *Hubble Space Telescope* (*HST*; Proposal SM2/ERO-7129). The images were retrieved from the Mikulski Archive for Space Telescopes (MAST).⁸ Individual images were combined in order to remove the cosmic rays using the *DrizzlePac* software (Gonzaga et al. 2012)⁹, with a resulting exposure time of 1280 s.

3. H_2 EMISSION

The H_2 (1-0) S(1) emission was first detected in NGC 2346 by Zuckerman & Gatley (1988) using a circular variable filter. Kastner et al. (1994), Vicini et al. (1999), and Arias et al. (2001) imaged the H_2 (1-0) S(1) emission in the whole nebula, with a seeing of about $2''.5$. They resolved the extended H_2 (1-0) S(1) emission in both the lobes and what they thought was a central torus. However, our much higher-resolution images show that this feature is not a smooth torus, but an aggregation of a large number of clumps. Vicini et al. (1999) also obtained spectra in the K -band, obtaining a ratio of the H_2 (1-0) S(1)/ H_2 (2-1) S(1) lines of about 14 in the central part and 4.3 in the lobes, while Arias et al. (2001) found a value of 6.6 for the torus. Our much better resolution images (see Figure 1) show that the H_2 (1-0) S(1) emission is in the form of clumps and cometary knots (see Figures 2 and 3), and are located in both the lobes and the central region. Clump sizes vary from $0''.16$ to $0''.34$ along the semimajor axis, and

⁷ Image Reduction and Analysis Facility (IRAF) software is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

⁸ <https://archive.stsci.edu/hst/>

⁹ http://www.stsci.edu/hst/HST_overview/drizzlepac/examples/example7/DrizzlePac_Ex7.pdf

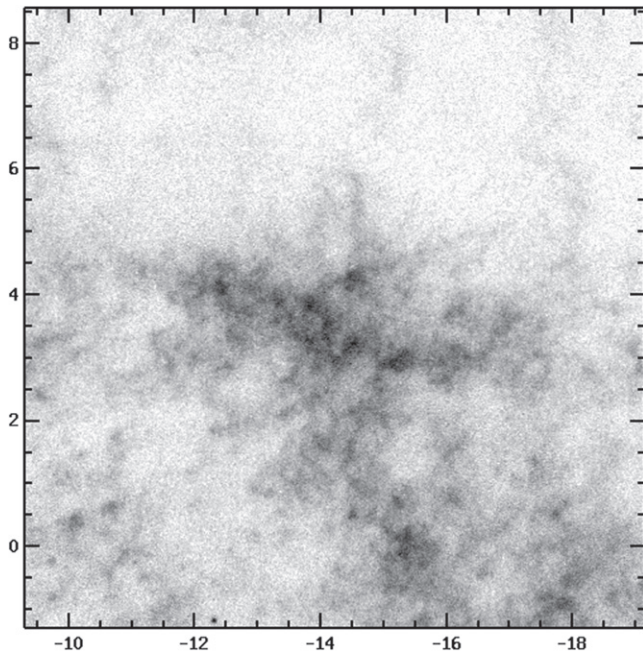


Figure 2. H_2 (1-0) S(1) clumps northwest of the central star.

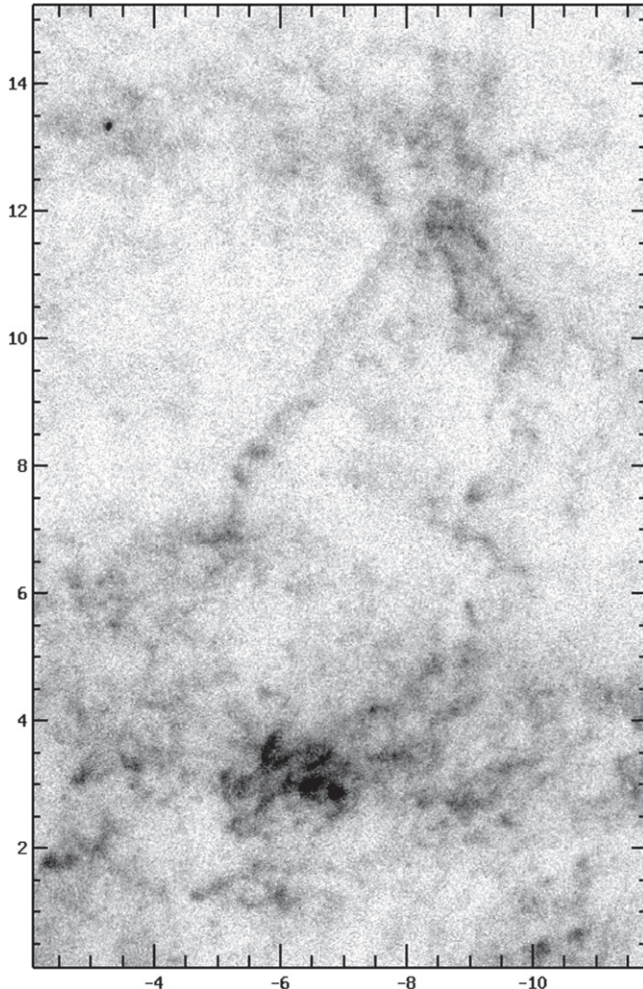


Figure 3. H_2 (1-0) S(1) cometary knot northwest of the central star.

Table 1
Masses and Separation of the Binary System

Inclination Angle (degree)	Progenitor Mass (M_{\odot})	Separation (AU)
30	0.72	0.167
35	0.61	0.166
38	0.56	0.165
40	0.53	0.164
50	0.43	0.162
60	0.37	0.161
70	0.34	0.160
80	0.33	0.159
85	0.32	0.159

projected distances from the central star are from $1''.6$ to $44''.2$. For the brightest clump we derive an H_2 (1-0) S(1)/ H_2 (2-1) S(1) line ratio of 4.7, which is consistent with the value derived by Vicini et al. (1999) for the lobes and by Arias et al. (2001) for the central region. From our H_2 (1-0) S(1) image we obtain line surface brightness of 8.8×10^{-4} and $1.8 \times 10^{-4} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for the brightest and weakest clumps, respectively. The highest value is nine times higher than Vicini et al. (1999) found. This is due to the dilution effect of their poor spatial resolution. If we degrade our H_2 (1-0) S(1) image to Vicini et al.'s (1999) spatial resolution ($3''$) we obtain a very similar value of $0.9 \times 10^{-4} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, compared with their value of $0.7 \pm 2 \times 10^{-4} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. The values that we find for the brightest clumps are 2.5 times higher than the predictions of Model 1 from Vicini et al. (1999) in the 3000–10,000 years interval and five times higher than the value that Speck et al. (2003) found in NGC 6720. Model 1 in Vicini et al. (1999) predicts H_2 (1-0) S(1) emission originating in the photodissociation region, created at the edge of the neutral shell by the UV radiation. Thus, our values seem to favor shock excitation. However, Vicini et al.'s (1999) model reproduced the average surface brightness and did not explore the full parameter space.

4. STELLAR PROGENITOR MASS

The central star of NGC 2346 is a spectroscopic binary (MN81) with a period of 15.99 days. The main-sequence companion of the ionizing star, which is seen in Figure 1, is a $1.8 M_{\odot}$ A5V star with $T_{\text{eff}} = 8000 \text{ K}$ and $L = 18 L_{\odot}$ (MN81). From the magnitude and extinction of the companion, MN81 obtained a distance of 700 pc to the system. The ultraviolet excess of the ionizing star is compatible with a white dwarf with $L = 50 L_{\odot}$ and $T_{\text{eff}} = 100,000 \text{ K}$.

The mass of the ionizing star carries the uncertainty in the unknown inclination angle of the binary orbit, but a reasonable assumption is to consider the orbital plane to be perpendicular to the bipolar lobes of the nebula and zero orbital eccentricity (Jones et al. 2010). Given the 120° inclination angle of the lobes with respect to the line of sight estimated by Arias et al. (2001), the binary orbital plane should be seen at an angle of $i = 60^\circ$ and within $35^\circ < i < 85^\circ$ using a 25° uncertainty (Arias et al. 2001). In Table 1 we list the solutions for the mass of the ionizing source and the separation of the two components using this plausible range of inclination angles for the binary system.

Using the plausible range of inclination angles, we obtain a mass range for the ionizing source between 0.32 and $0.72 M_{\odot}$. The binary separation, which has a very small dependency on the inclination assumed, has values ranging from 0.159 to 0.167 AU (34.2 – $35.7 R_{\odot}$). The ionizing star must have evolved past the giant phase, reaching a radius (either on the red giant or on the AGB) much larger than the current orbital separation of the system. Thus, it is very likely that the binary system experienced orbital decay if it suffered CE evolution, but significant orbital decay is not expected if instead mass was simply transferred from the primary when the giant's envelope was not fully convective. The evolution of a binary system through the CE phase is not understood in detail, and thus it is difficult to infer the precise history of individual systems (see, e.g., Ivanova et al. 2013). Given the orbital parameters of the known components and the mass of the main-sequence companion to the PN progenitor, there are two reasonable assumptions we can make regarding the past history of this system: (i) the evolution of the binary did not result in a merger; and (ii) the main-sequence mass of the PN progenitor must have been greater than $1.8 M_{\odot}$ for it to have evolved into a giant before its companion.

It is difficult to estimate the amount of mass accumulated by the secondary. Note that the fraction of the envelope that was lost in the CE evolution is unknown. Therefore we can only set a lower limit to the initial mass of the PN progenitor. Likewise, we have to assume that the initial orbit separation was larger than 0.16 AU. But since the spectrum of the ionizing source is unknown, we are unable to determine with certainty whether the CE phase occurred during the progenitor's red giant branch (RGB) or AGB evolution. However, we argue that the CE phase must have occurred in the AGB, since the orbital separation is expected to decrease during CE evolution (Webbink 1984) and considering that the largest core mass that can build up during the RGB is $\approx 0.47 M_{\odot}$ (see, e.g., Sweigart et al. 1990). This would give the progenitor enough time to build up a large enough CO core to sustain the photoionization of the nebula.

Davis et al. (2010), using population synthesis techniques, modeled a CE system to obtain ZAMS progenitor masses of $2.47 M_{\odot}$ and $0.98 M_{\odot}$, and a final WD configuration with a mass $0.33 M_{\odot}$. However, such a small WD mass cannot sustain the ionization of the nebula and it is not consistent with the UV emission observed. A more massive primary that experienced enhanced mass loss before it filled its Roche lobe was suggested by Tout & Eggleton (1988) for this system.

Since the companion has a mass of $1.8 M_{\odot}$, we can set this value as the lower limit to the PN progenitor mass. From Vassiliadis & Wood (1993) this value is consistent with $L = 50 L_{\odot}$ and $T_{\text{eff}} = 100,000$ K. Thus, the most plausible solution for the progenitor is a $1.8 M_{\odot}$ star that has experienced CE evolution on the AGB, leaving a remnant greater than $0.61 M_{\odot}$.

We computed the number of ionizing photons for a $1.8 M_{\odot}$ star assuming a blackbody spectrum, $\log L/L_{\odot} = 1.730$, and $T_{\text{eff}} = 93,540$ K, to be 4.0×10^{45} photons s^{-1} . We will use this result in the modeling described in the next section.

5. DISCUSSION

5.1. Analysis of the Clumps

As can be seen in Figures 1 through 4, the H_2 emission is clumpy. This clumpy structure contrasts, as expected, with the

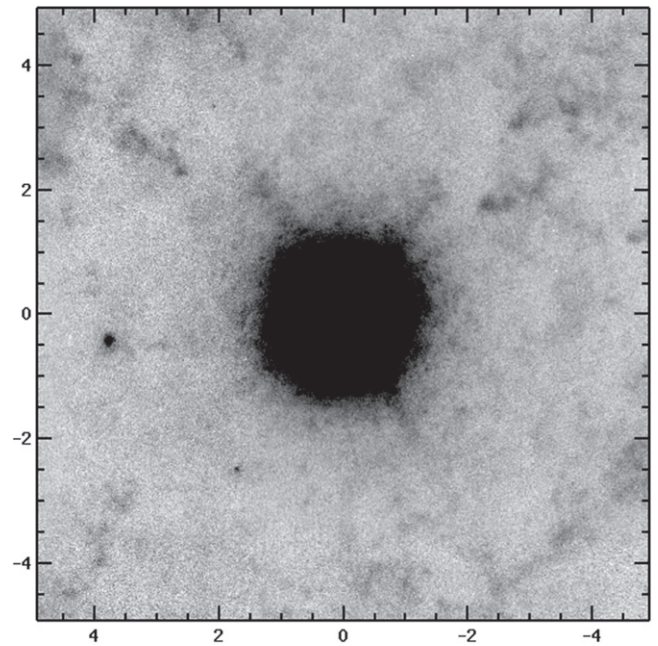


Figure 4. H_2 (1-0) S(1) cometary knots close to the central star.

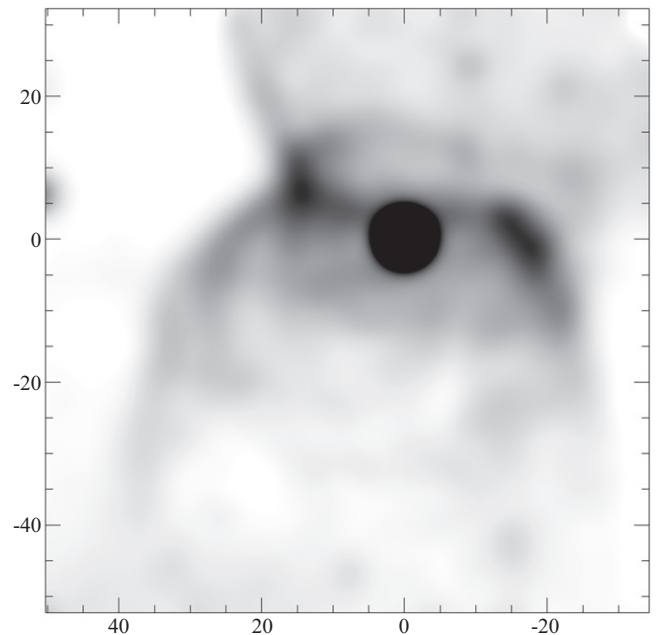


Figure 5. Same as Figure 1, but convolved with a PSF with a spatial resolution of 2 arcsec.

smoother structure seen in the ionized gas (Figure 1). Our high-resolution images clearly show that the H_2 emission is not uniformly distributed in a torus around the central star as it has been interpreted from previous lower-resolution observations, but displays a fragmented structure mainly composed of clumps and cometary knots. To further probe this point we convolved our H_2 (1-0) S(1) image with a symmetric PSF of $2''$, as shown in Figure 5. It is easy to see how the presence of a torus around the central star might be inferred from a lower-resolution image. Most of the clumps are generally superimposed on a diffuse emission (see Figures 1 through 4). They are sometimes grouped as in Figure 2, have cometary tails as in Figure 3, or have a bow shock shape as in Figure 4. All of this

makes it very difficult to measure the number and distribution of clumps in the nebula (e.g., the total number of clumps, radial distribution, fluxes, and knot structure). In any case, the H_2 (1-0) S(1) distribution in NGC 2346 is completely different than the one in NGC 7293 (Matsuura et al. 2009). Assuming a distance of 700 pc, each pixel in our image corresponds to a physical size of 14 AU. From Figure 1 we find that most of the knots are concentrated on the waist of the nebula (east–west), and at the edges of the lobes. In the lobes, at distances further than 0.02 pc from the central star, the H_2 emission is more diffuse. The clumps are at distances of 0.0089–0.15 pc from the central star. Typical sizes are in the $1.67\text{--}3.52 \times 10^{15}$ cm (112–238 AU) range.

5.2. Formation of the Clumps

Several mechanisms have been explored to explain the formation of molecular clumps and cometary tails in PNs. A scenario in which preexisting high-density structures in the ISM are responsible for the structures observed (Al  zas et al. 2012) is difficult to rule out a priori. The question is then how the ISM high-density clumps were formed in the first place. The mechanism proposed by Garc  a-Segura et al. (2006) provides a solution for both the formation of the observed H_2 clumps in the PN and the possible existence of long-life high-density clumps in the ISM. In addition, when high-resolution observations of H_2 in PNs are obtained, they often reveal clumpy structures (M  rquez-Lugo et al. 2013). To assume that the ejected AGB shell would always encounter a clumpy ISM does not seem reasonable; it would imply the ISM to be densely populated by high-density structures along many lines of sight. We prefer the more plausible explanation offered by Garc  a-Segura et al. (1999) that Rayleigh–Taylor instabilities, or the effects of the ionizing radiation in the nebula, lead to the formation of clumps. Garc  a-Segura et al. (2006) proposed that the cessation of a fast stellar wind can self-consistently produce the type of fragmented structures we observed in NGC 2346. The mechanism only requires a rapid decline (i.e., switching off) of the fast stellar wind in an ionization-bounded PN. If the stellar wind becomes negligible, the hot, shocked bubble depressurizes and the thermal pressure of the photoionized region at the inner edge of the swept-up shell becomes dominant. The shell tends to fragment, creating clumps of neutral gas with comet-like tails and long, photoionized trails in-between, while the photoionized material expands back toward the central star. In the hydrodynamical simulations by Garc  a-Segura et al. (2006) the cometary globules originate in the neutral, swept-up shell of piled up AGB wind and so they must be excited by shocks.

There are two mechanisms, arising in very different physical conditions, that can be responsible for the observed H_2 emission: (i) shock excitation (Shull & Hollenbach 1978) or (ii) UV pumping in photodissociation regions (e.g., Black & van Dishoeck 1987). Arias et al. (2001) explored the nature of the excitation in NGC 2346 using the relative intensities of the H_2 (1-0) S(1) and H_2 (2-1) S(1) lines and concluded that the H_2 emission line ratios are consistent with shock excitation, both in the central nebular regions and in the lobes. Further support for shock excitation comes from the incompatibility of H_2 (1-0) S(1) flux with UV excitation, which is described in Section 3.

Since the spectrum of the central star is unknown, we cannot determine for certain if the antecedent fast wind has decayed, leading to depressurization of the hot bubble. However, there is

some evidence of this being the case. First, the central star is relatively massive, so the wind would be expected to evolve quickly (Villaver et al. 2002). Second, in spite of moderate interstellar extinction, if a robust fast wind were present one would expect X-ray emission. Yet NGC 2346 has not been detected with either *XMM* imaging (Gruendl et al. 2006) nor *Chandra* observations (Kastner et al. 2012). Furthermore, orbital decay is compatible with the nebula kinematical age (>3500 years) derived by Arias et al. (2001), which, according to Villaver et al. (2002), is evidence that the fast wind has already declined below its maximum kinetic energy.

To further examine the formation of the clumps, we have used the three dimensional (3D) version of the Garc  a-Segura et al. (2006) model, with AGB wind velocity $v_{\text{exp}} = 10 \text{ km s}^{-1}$, AGB mass loss $\dot{M} = 10^{-5} M_{\odot} \text{ yr}^{-1}$, fast wind velocity $v_{\text{exp}} = 1000 \text{ km s}^{-1}$, and fast wind mass loss $\dot{M} = 10^{-7} M_{\odot} \text{ yr}^{-1}$. The temporal grid has 125^3 zones, and physical dimensions $0.8 \times 0.8 \times 0.8 \text{ pc}$. The fast wind was terminated in the simulation at 1000 years from the onset. The photoionization follows the prescription of Garc  a-Segura & Franco (1996), assuming a central ionizing emission of 10^{45} s^{-1} ionizing photons (see above). To obtain bipolarity, we assumed that the rotation velocity approached 95% of its critical value, following Garc  a-Segura et al. (1999). The simulation was performed using the hydrodynamical code ZEUS-3D (Norman 2000). It must be noted here that this simulation is highly qualitative due to the following factors: (1) the grid resolution was low and (2) the simulation was not tailored to explain NGC 2346 in detail but instead used standard average parameters (although the model was optimized for NGC 2346 in that it assumed a similar number of photoionizing photons as those derived from the NGC 2346’s UV flux). Nevertheless, this model is useful for understanding clump formation.

In Figure 6 we show the gas emission measure for nine model snapshots, on the X – Z plane. The initial model is for $t = 1000$ years (following the termination of the fast stellar wind) and subsequent models are at timestep of 1000 years, covering 9000 years of the evolution. The emissions of the various components are represented by different colors: photoionized gas with temperatures $\sim 10,000 \text{ K}$ is represented in green; gas (either photoionized or neutral) with temperatures above 1000 K is in red, and gas with temperatures below 1000 K (blue). The blue (cool) gas emission follows the molecular emission (i.e., H_2), so we can use this latter indicator to see what happens in the molecular regime. The simulation shows, as a general view, an initial toroid of cool gas at the equator. Once the swept-up shell is highly fragmented, the toroid is no longer visible and only the large clumps with an optical depth big enough to shield the ionizing radiation will survive and be detected.

The current evolutionary stage of NGC 2346 is represented by models of times between the first and the second snapshot of Figure 6, since it appears that the clumps in NGC 2346 are just being formed, and the photoionization front has not yet reached the equatorial latitudes. NGC 2346 has a small number of long cometary knots (Figure 3), not easily recognizable in the *HST* [N II] image (Figure 1). This contrasts with the large number of such knots in the Helix (NGC 7293) or in the Eskimo (NGC 2392) nebulae (O’Dell et al. 2002). In addition the size of the clumps in NGC 7293 (94 AU) are similar in size to those in NGC 2346 (O’Dell et al. 2007).

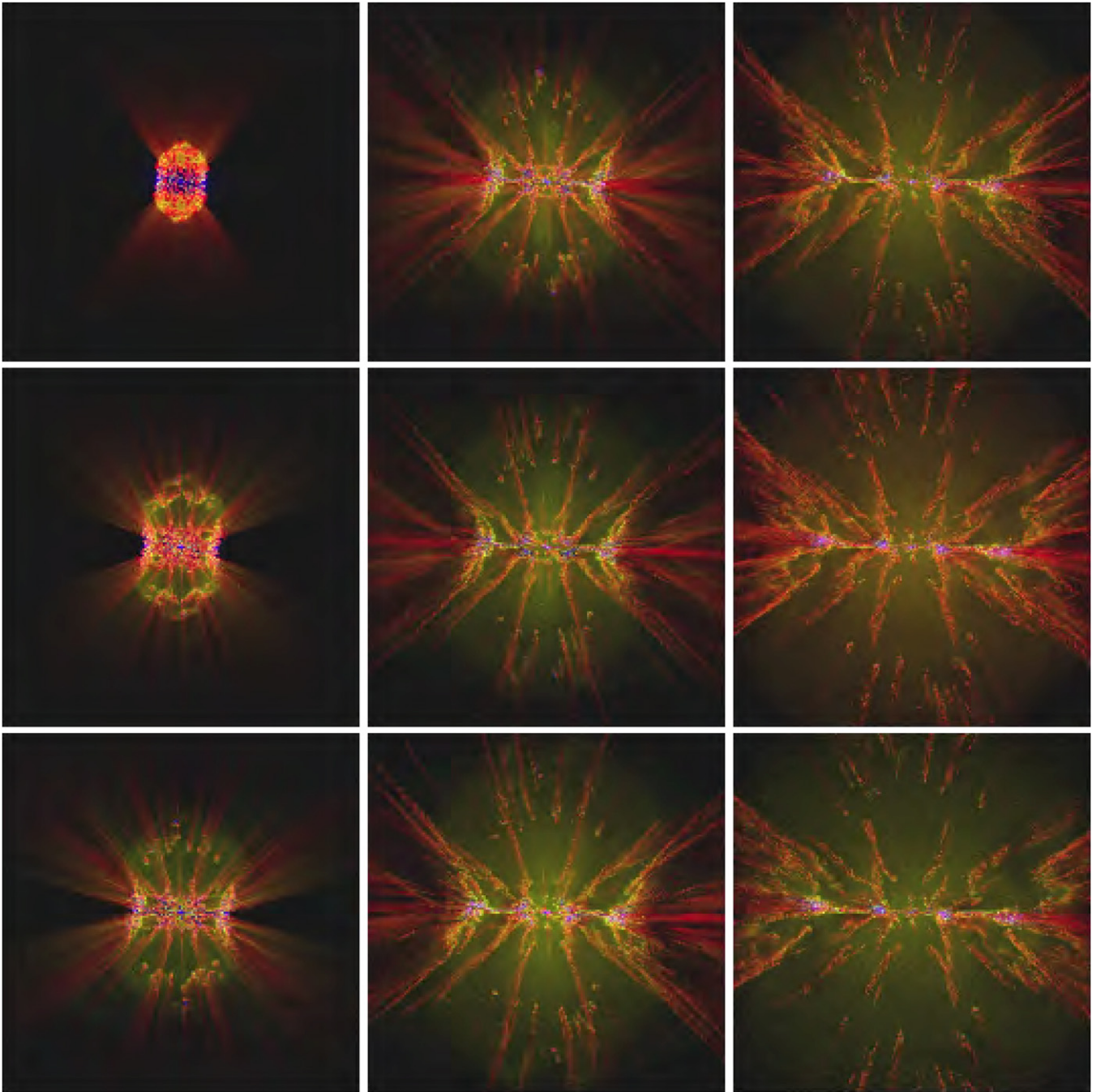


Figure 6. Snapshots of the emission measure ($\text{cm}^{-6} \text{ pc}$) along the line sight of the modeled gas. Three different temperatures are represented in different colors (see the text for details). Starting at 1000 years of elapsed time with the cessation of the stellar wind (upper left), the evolution proceeds from upper to lower, then left to right, with a timestep of 1000 years.

5.3. The Survival of H_2 Clumps

An interesting question is to determine how the molecular hydrogen clumps can survive the photoionization front. If the propagation velocity dR/dt of the ionization front within a clump can be expressed according to Equation (7.5) of Dyson & Williams (1997), then

$$\frac{dR}{dt} = \frac{S_*}{4\pi R^2 n_0} - \frac{1}{3} R n_0 \beta_2, \quad (1)$$

where S_* is the number of photoionizing photons, R is the distance from the ionizing source to the clump, dR is the size of

the clump, β_2 is the recombination coefficient, and n_0 is the density of the clumps. For NGC 2346, the closest clumps (see Figure 4) are at a projected distance of $2.75 \times 10^{16} \text{ cm}$ (1850 AU) from the central star, with sizes $\sim 2.1 \times 10^{15} \text{ cm}$. Thus, assuming $S_* = 4.0 \times 10^{45} \text{ s}^{-1}$ and the kinematical age as a proxy for the evolutionary time (3500 years), we estimate the minimum density required for clumps to survive the passage of the ionization front. We obtain a value of $n_0 = 15,000 \text{ cm}^{-3}$, which is smaller than that of the gas density derived for the largest clumps ($5 \times 10^4 \text{ cm}^{-3}$) from dust absorption of the [O III] images in NGC 6853 by Meaburn & López (1993).

During post-AGB evolution the stellar luminosity declines, and some nebular clumps may not be photoionized. Instead, they survive as molecular material, eventually making the ISM clumpy. Since the H_2 (1-0) S(1) will not couple with the 3 K cosmic microwave background, the only destructive mechanism in the ISM is the spontaneous radiative dissociation (Stephens & Dalgarno 1972). Pflamminger et al. (1994) proposed that H_2 clumps of a size of about 30 AU can explain baryonic dark matter in spiral galaxies. The H_2 clumps in NGC 2346 with sizes between 112 and 238 AU will populate the ISM, contributing to the baryonic dark matter of the Galaxy. Whether or not H_2 (1-0) S(1) in clumps survive past the PN stage and populate the ISM of galaxies is beyond the scope of this work. We speculate that if clumps survive, given the amount of mass they contain, they should be accounted for as a source of baryonic dark matter.

6. CONCLUSIONS

We have obtained molecular hydrogen (H_2) images of NGC 2346 with unprecedented spatial resolution: 56 AU at an adopted distance of 700 pc. The images reveal the H_2 emission to be fragmented into clumps and cometary knots, rather than joined as a uniform disk as previously thought. The clumps range in size from 112 to 238 AU; the clump apparently closest to the central star lies at a projected distance of 1850 AU. The central star has undergone binary interaction with its nearby companion, probably during its AGB phase. The ionizing star has a minimum mass of $0.61 M_\odot$, and an ionizing flux of $4.0 \times 10^{45} \text{ photons s}^{-1}$.

We performed a hydrodynamical simulation that shows how an initial disk or toroid breaks up into individual clumps once the swept-up shell fragments following the decline of the fast wind. In order to survive the ionization front, the pre-ionization density of the molecular hydrogen clumps must exceed $\sim 15,000 \text{ cm}^{-3}$, which is found in some PNs. Those clumps that survive the ionization front will eventually populate the ISM and may contribute to the baryonic dark matter in our Galaxy.

We are grateful to R. Carrasco for the data reduction of the GSAOI images. We thank Wolfgang Steffen and Dolores Bello for fruitful discussion. A.M. and D.A.G.H. acknowledge support for this work provided by the Spanish Ministry of Economy and Competitiveness under grant AYA-2011-27754. L.S. and R.A.S. acknowledge support for this project from NOAO. E.V. acknowledges support from grant AYA 2013-45347P. G.G.-S. is partially supported by CONACyT grant 178253 and DGAPA grant IN100410. G.G.-S. thanks Michael L. Norman and the Laboratory for Computational Astrophysics for the use of ZEUS-3D. Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-*HST* data is provided by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts. This work is based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National

Science Foundation (United States), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), Ministério da Ciência, Tecnologia e Inovação (Brazil), and Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina).

REFERENCES

- Alúzar, R., Pittard, J. M., Hartquist, T. W., Falle, S. A. E. G., & Langton, R. 2012, *MNRAS*, **425**, 2212
- Arias, L., Rosado, M., Salas, L., & Cruz-González, I. 2001, *AJ*, **122**, 3293
- Black, J. H., & van Dishoeck, E. F. 1987, *ApJ*, **322**, 412
- Carrasco, E. R., Edwards, M. L., McGregor, P. J., et al. 2012, *Proc. SPIE*, **8447**, 84470N
- Corradi, R. L. M., Rodríguez-Gil, P., Jones, D., et al. 2014, *MNRAS*, **441**, 2799
- Davis, P. J., Kolb, U., & Willems, B. 2010, *MNRAS*, **403**, 179
- de Kool, M., & Ritter, H. 1993, *A&A*, **267**, 397
- De Marco, O., Passy, J.-C., Frew, D. J., Moe, M., & Jacoby, G. H. 2013, *MNRAS*, **428**, 2118
- Dyson, J. E., & Williams, D. A. (ed.) 1997, *The Physics of the Interstellar Medium* (2nd ed.; Bristol, UK: Institute of Physics Publishing), 115
- García-Segura, G., & Franco, J. 1996, *ApJ*, **469**, 171
- García-Segura, G., Langer, N., Różyńska, M., & Franco, J. 1999, *ApJ*, **517**, 767
- García-Segura, G., López, J. A., Steffen, W., Meaburn, J., & Machado, A. 2006, *ApJL*, **646**, L61
- Gonzaga, S., Hack, W., Fruchter, A., & Mack, J. (ed.) 2012, *The DrizzlePac Handbook* (Baltimore: STScI)
- Gruendl, R. A., Guerrero, M. A., Chu, Y.-H., & Williams, R. M. 2006, *ApJ*, **653**, 339
- Huggins, P. J., Forveille, T., Bachiller, R., et al. 2002, *ApJL*, **573**, L55
- Huggins, P. J., & Maun, N. 2002, *A&A*, **393**, 273
- Ivanova, N., Justham, S., Chen, X., et al. 2013, *A&ARv*, **21**, 59
- Jones, D., Lloyd, M., Santander-García, M., et al. 2010, *MNRAS*, **408**, 2312
- Kastner, J. H., Gatley, I., Merrill, K. M., Probst, R., & Weintraub, D. 1994, *ApJ*, **421**, 600
- Kastner, J. H., Montez, R., Jr., Balick, B., et al. 2012, *AJ*, **144**, 58
- Kastner, J. H., Weintraub, D. A., Gatley, I., Merrill, K. M., & Probst, R. G. 1996, *ApJ*, **462**, 777
- Latter, W. B., Kelly, D. M., Hora, J. L., & Deutsch, L. K. 1995, *ApJS*, **100**, 159
- Márquez-Lugo, R. A., Ramos-Larios, G., Guerrero, M. A., & Vázquez, R. 2013, *MNRAS*, **429**, 973
- Matsuura, M., Speck, A. K., McHunu, B. M., et al. 2009, *ApJ*, **700**, 1067
- McGregor, P., Hart, J., Stefanovic, D., et al. 2004, *Proc. SPIE*, **5492**, 1033
- Meaburn, J., & López, J. A. 1993, *MNRAS*, **263**, 890
- Méndez, R. H., & Niemela, V. S. 1981, *ApJ*, **250**, 240 (MN81)
- Miszalski, B., Boffin, H. M. J., & Corradi, R. L. M. 2013, *MNRAS*, **428**, L39
- Neichel, B., Rigaut, F., Vidal, F., et al. 2014, *MNRAS*, **440**, 1002
- Norman, M. L. 2000, *RMxAC*, **9**, 66
- O'Dell, C. R., Balick, B., Hajian, A. R., Henney, W. J., & Burkert, A. 2002, *AJ*, **123**, 3329
- O'Dell, C. R., Henney, W. J., & Ferland, G. J. 2007, *AJ*, **133**, 2343
- Pflamminger, D., Combes, F., & Martinet, L. 1994, *A&A*, **285**, 79
- Redman, M. P., Viti, S., Cau, P., & Williams, D. A. 2003, *MNRAS*, **345**, 1291
- Ricker, P. M., & Taam, R. E. 2012, *ApJ*, **746**, 74
- Rigaut, F., Neichel, B., Boccas, M., et al. 2014, *MNRAS*, **437**, 2361
- Sandquist, E. L., Taam, R. E., Chen, X., Bodenheimer, P., & Burkert, A. 1998, *ApJ*, **500**, 909
- Shull, J. M., & Hollenbach, D. J. 1978, *ApJ*, **220**, 525
- Soker, N. 1998, *MNRAS*, **299**, 562
- Speck, A. K., Meixner, M., Jacoby, G. H., & Knezek, P. M. 2003, *PASP*, **115**, 170
- Stephens, T. L., & Dalgarno, A. 1972, *JQSRT*, **12**, 569/586
- Sweigart, A. V., Greggio, L., & Renzini, A. 1990, *ApJ*, **364**, 527
- Tout, C. A., & Eggleton, P. P. 1988, *MNRAS*, **231**, 823
- Vassiliadis, E., & Wood, P. 1993, *ApJ*, **413**, 641
- Vicini, B., Natta, A., Marconi, A., et al. 1999, *A&A*, **342**, 823
- Villaver, E., Machado, A., & García-Segura, G. 2002, *ApJ*, **581**, 1204
- Webbink, R. F. 1984, *ApJ*, **277**, 355
- Zuckerman, B., & Gatley, I. 1988, *ApJ*, **324**, 501