Journal of the Southeastern Association for Research in Astronomy, 5, 19–24, 2012 February 1

MODELING BINARY CENTRAL STARS OF PLANETARY NEBULAE II: A STUDY OF HATR 4 AND SP 1

Eva H. L. Bodman[1]
Department of Physics, Syracuse University, NY, 13210

and

Sam Clay Schaub[1]
Department of Physics and Astronomy, Valparaiso University, IN, 46383

and

Todd Hillwig
Department of Physics and Astronomy, Valparaiso University, IN, 46383

ABSTRACT

We have modeled the binary central star systems of the planetary nebulae HaTr 4 and Sp 1. The models are based on light curves from data taken over several years. A large parameter space has been explored to find constraints on the systems' characteristics. Some limitations have been made on the parameter space from values found in literature. The focus of the limitations is on the mass, radius, and temperature of the central star, the type of companion star, and the inclination of the system since these are the most important physical properties of the system. The temperature and radius of both stars and the inclination also affect the shape of the light curve. The binary hypothesis is based on the premise that binary star systems cause the non-spherical shape of planetary nebulae. The hypothesis predicts a correlation between the system's inclination and the nebula's inclination. We constrained the inclination of Sp 1 between 15° and 25°. For HaTr 4, we constrained the inclination between 50° and 85° but found most of the best fits between 55° and 75°. The published values for the HaTr 4 nebular inclination fall within our calculated ranges for the binary inclination. For Sp 1, the published nebular inclination values fall just outside our modeled binary inclination range.

Subject headings: binaries: close — planetary nebula: bipolar — planetary nebula: individual (Sp 1, HaTr 4)

1. INTRODUCTION

A planetary nebula (PN) is the last stage in an intermediate-mass star's evolution before it fades into a white dwarf. Stars form a PN when the outer layers of their atmospheres have been blown off by high speed winds and the hot cores left to contract. The ejected gas compresses as it collides with the slower moving dust and gas lost in earlier stages of stellar evolution. The very hot, contracting central star (CS) of the PN ionizes the resulting shell of gas. Eventually, the nebula expands so much that it cools and fades away leaving a white dwarf. The visible nebula stage is short ($\sim$ 50000 yrs) which means we see relatively few PNe compared to the number of intermediate-mass stars.

Each PN is unique in shape and color, but nebulae morphologies can be put into categories based on their symmetry. PNe are usually categorized by their two dimensional projection. However, with a three dimensional model based on radial velocities the nebular structure can be described more accurately. Common categories used are round, elliptical, bipolar, irregular and point symmetric. Round and elliptical nebulae are shaped like their names imply. Some nebulae look round, but they may actually be bipolar nebulae viewed pole on like Sp 1(Mitchell et al. 2006). Elliptical nebulae, including round nebulae, make up the majority of nebulae (Corradi & Schwarz 1994). Bipolar nebulae have two axes of symmetry and are shaped like a tube with a cinched waist in three dimensions. Often the ends flare out making the nebula look vaguely like a butterfly which is what bipolar nebulae are sometimes called. Irregular nebulae have no axes or points of symmetry. Point symmetric nebulae have a point of symmetry at the geometrical center. Bipolar and irregular nebulae occur at about the same rate and point symmetric nebulae are rare (Corradi & Schwarz 1994).

Round nebulae can be explained by isotropic fast winds colliding with older, slower winds from an earlier stage of stellar evolution (Frank, Balick & Riley 1990). Stellar rotation, the contribution of magnetic fields, and other properties of the star complicate the wind interaction, meaning that winds are almost certainly not isotropic. If the winds are not assumed to be isotropic, slightly elliptical nebulae can be explained by the wind theory of formation (Balick & Frank 2002). The more complicated shapes are more difficult to explain and debate over their origins continues.

Bipolar nebulae consist of two opposing lobes with a dense torus at the center. The dense torus deflects high speed winds to the poles, creating the expanding lobes. The origin of the lobes is debated. One theory of the origin of the bipolar shape is due to magnetic fields. A fast rotating star produces strong magnetic fields that affect the ionized matter in the nebula, forming the shape. But as the magnetic field changes the nebula's shape, the star loses the angular momentum that powers the

Electronic address: ehbodman@syr.edu
[1] Southeastern Association for Research in Astronomy (SARA) NSF-REU Summer Intern

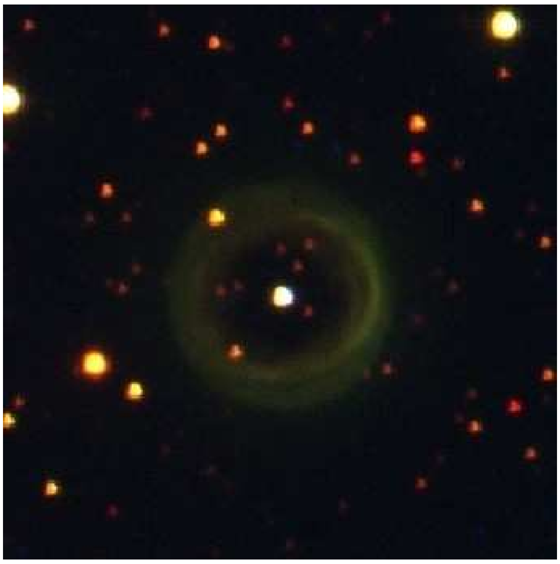

FIG. 1.— Image of Sp 1 taken at the SARA South 0.9m telescope. The circular ring would normal result in a 'round' classification for the nebula but models suggest that the three-dimensional structure to be a tube shape seen nearly pole-on (Mitchell et al. 2006).

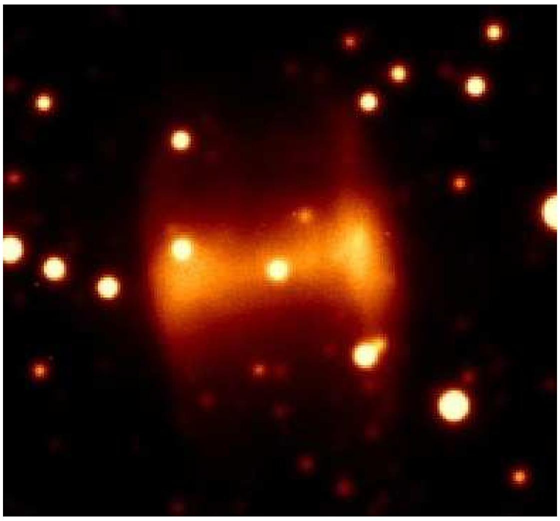

FIG. 2.— False color image of HaTr 4 from the ESO NTT archive. The bright band is the denser center of a faded nebula. The nebula is probably elliptical.

magnetic fields. A single star cannot maintain the angular momentum needed to support the magnetic field long enough to form the bipolar shape (De Marco 2009). In the binary hypothesis a companion star can add the needed angular momentum to the system to maintain the strong magnetic field. Binary companions also can form a disk around the system which aids the formation of the lobes. Substellar mass objects such as brown dwarfs and large mass planets can also provide the necessary shaping effects. However, in surveys, only 10-20% of the CSs are detected as close binaries of which the large majority have periods of less than 3 days (De Marco, Hillwig, & Smith 2008; Miszalski et al. 2009). This percentage is too low to explain all bipolar nebulae but the survey estimates may be too low because of limitations in detection. More complicated shapes of nebulae exist, such as point-symmetric nebulae, which call for additional theoretical aspects (e.g. precession) typically requiring a binary companion.

The search for binary companions to the CSs of PNe (CSPNe) begins with finding light variations in the stars. Typical causes for light variability are (1) eclipses, during which one star passes in front of the other, (2) an irradiation effect caused by the hot CS heating the facing hemisphere of a cool companion, and (3) an ellipsoidal effect due to one or both stars filling a significant fraction of their Roche lobe, thus being distorted from a spherical shape. For eclipses, typically two eclipses are seen per orbit, though for large temperature differences the eclipse of the cool star my require very high precision data to detect. An irradiation effect exhibits one cycle per orbit as the heated hemisphere orbits into and out of our line of sight. Ellipsoidal effects result in two cycles per orbit due to the projected surface area of the deformed star changing as it orbits.

Using the photometric variability method finds only close binary companions, forming a bias in the sample. Also, a binary system does not need to be close to affect the shaping of the nebulae (De Marco 2009). Light variations are also only detectable if the period of the variation is less than a week because the irradiation effect does not produce large enough amplitudes in variation to be easily detectable at larger periods (De Marco et al. 2008). This limits the statistical accuracy of the surveys of CSPNe. The actual percentage of binary companions could be higher than observed by this method. It is from a sample of binary stars found to be variable from the irradiation effect and with known periods and light curves that we chose bipolar PNe Sp 1 and HaTr 4 for further study (see figures 1 and 2).

Other than finding binary systems, the binary hypothesis is tested by modeling known systems and comparing the results to the predictions. We expect that the physical properties of the central binary star determine the shape of the nebula so modeling the binary systems gives clues to the process. Models cannot determine the central properties exactly but they can constrain the ranges. If the ranges are small enough, we can determine if the predicted values fit the data. One physical parameter of the binary system that we focused on is the binary system inclination. According the binary hypothesis, matter is denser in the orbital plane so the winds expand more easily along the poles and form lobes there. This means the inclination of the nebula should match the inclination of the binary system. Modeling light curves narrows the range of inclinations that the binary system could have. We found this range with modeling along with ranges for other important physical parameters such as temperature and radius. Figures 1 and 2 are images of the PNe we study here. The ring of Sp 1 is the end on view of a tube, similar to a biploar nebula. The nebula of HaTr 4 is possibly the central waist of a bipolar nebula where the lobes have faded away.

2. METHOD

We used Binary Maker 3 to make models of the binary systems in Sp 1 and HaTr 4. Binary Maker 3 makes a three dimensional visual model of the system, a light curve and a radial velocity plot of the system. Since we had no radial velocity data, that part of the program was not used. Our modeling was done with light curve plotting only. Light curves were made on a linear flux

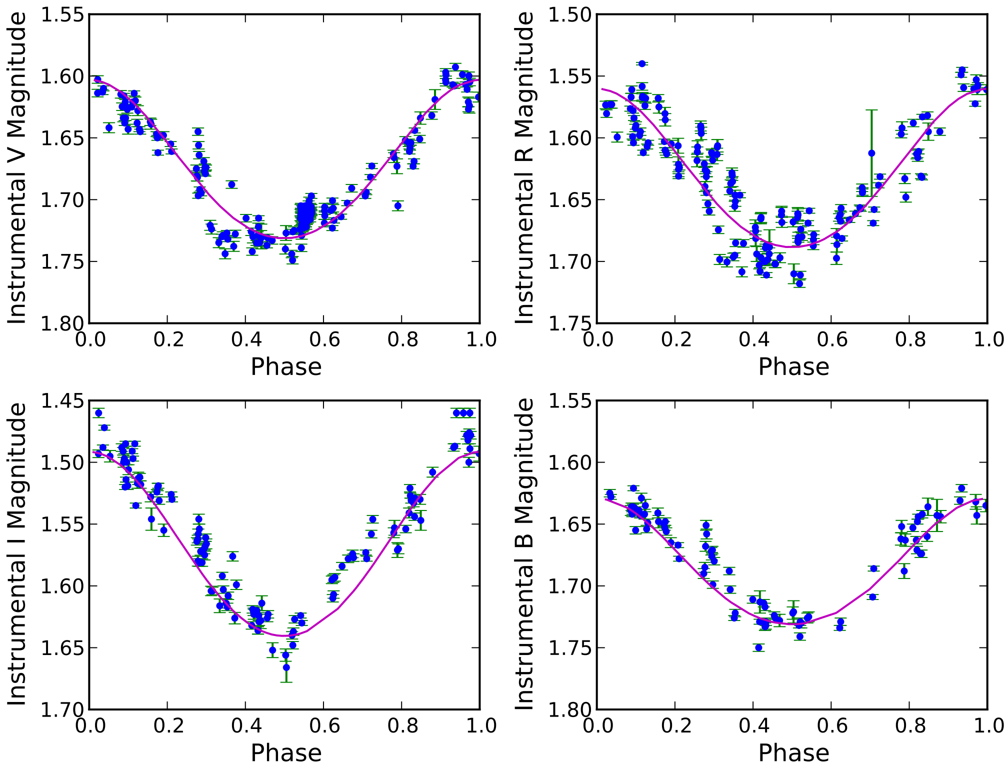

FIG. 3.— Clockwise from top left, the filters of the data and models of Sp 1 are V, R, B and I_c. This model is with a standard F8 main sequence star as a companion. Values are in Table 1. The inclination of the system is 18°.

scale. Our data were in magnitude and phase format which Binary Maker automatically converted into flux and phase. The visual models were used as a check if the input parameters were reasonable, especially in the case of the radius overflowing the Roche lobe.

Binary Maker uses many input parameters to create models. The basic parameters that were the focus of our study were radius and temperature of the central and companion stars, the mass ratio (m_2/m_1), and the inclination. Before we started modeling the CSPNe, many practice models were made to test the effects of changing the parameters. Temperature would affect the amplitude of the light curve. Increasing the temperature increases the amplitude. Changing the radius of the CS also changes the amplitude. Decreasing the radius increases the amplitude up to a maximum then the amplitude would decrease. Inclination changes the amplitude and also the shape of the curve. At inclinations over 40°, the curve is clearly not sinusoidal. Under 40°, the curve is approximately a sine curve. Increasing the inclination leads to an increasing deviation between the model and a sinusoid and also increases the amplitude. For more information on Binary Maker 3 and the parameter effects, see Schaub, Bodman & Hillwig (2010), hereafter Paper I.

3. MODELS

We made working models of Sp 1 and HaTr 4 in multiple filters. For Sp 1, we had data in BVR and I filters. We only had data in the V and R filters for HaTr 4. Since Binary Maker 3 makes light curves in relative fluxes, the models were converted to relative magnitudes so they can be combined with the data in magnitude plots for this paper. Since the models were compared to the data by eye, the values we state should be taken with caution. These binary models are a starting point for further research.

TABLE 1
SP 1 PARAMETERS

Parameter	Values
$T_{\rm CS}$ (K)	72,000
$R_{\rm CS}$ ($R_\odot$)	0.332
$M_{\rm CS}(M_\odot)$	0.56
$T_{\rm Comp}$ (K)	5900-6100
$R_{\rm Comp}(R_\odot)$	1.12-1.20
$M_{\rm Comp}(M_\odot)$	1.16-1.25

REFERENCES. — Gray (2005)

3.1. *Sp 1*

The nebula of Sp 1 looks round but preliminary kinematic studies have shown that the nebula is likely to be bipolar viewed pole on (Mitchell et al. 2006). With this idea, Miszalski et al. (2009) made simple three dimensional models of a bipolar nebula at different inclinations. Comparing by eye, they found that Sp 1 matched with a 5° inclination. While this method is not precise, it gives us a value to compare to our binary inclination.

The CS of Sp 1 was found to be variable by Bond and Livio (1990) with a period of 2.91 days and does not eclipse. The magnitude varies by about 0.15 in the V

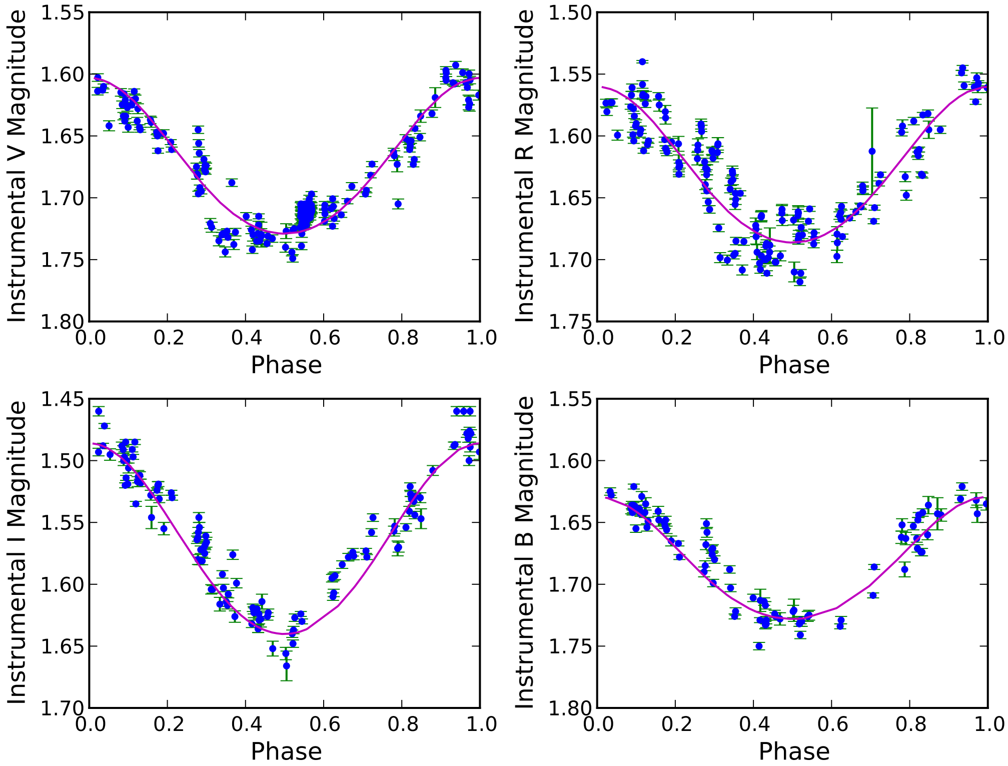

FIG. 4.— These are models and data for Sp 1 with filters in the same order as Fig. 3. This model is with a standard G0 main sequence star as a companion. Values are in Table 1. The inclination of the system is 19°.

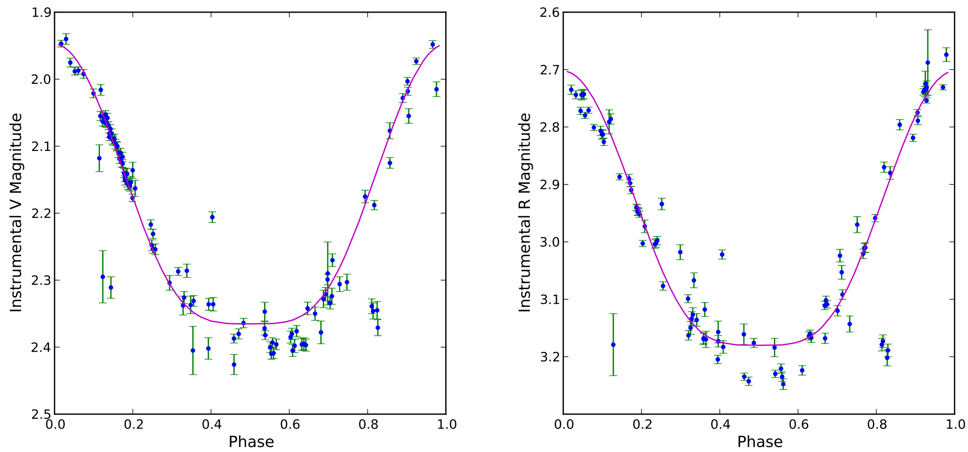

FIG. 5.— From left to right, the filters of the data and models of HaTr 4 are V and R. The companion star in this model is a G8 main sequence star. The parameters used for the CSPN are 67,000K, $0.1R_{\odot}$, aand $0.7M_{\odot}$. The inclination of the system is 81°.

filter in a sinusoid. The symmetry of the shape aided the modeling of the system as it constrained the inclination. Frew (2008) reports properties of the CS that are useful to modeling. The temperature was found to be 72,000 K by the Zanstra method. The mass was calculated to be 0.56 $M_{\odot}$. Frew also found the luminosity of the CS to be 2750 $L_{\odot}$. With the temperature and luminosity known, we calculated a radius for the CS.

The parameter space for the CSPN of Sp 1 was constrained greatly because of values from the literature. We limited the parameter space to the values found by Frew (2008). The values used are listed in Table 1 where the CS subscript refers to the hot central star and "Comp" refers to the cool companion. As a starting point we did not vary these input parameters. For the companion stars, we restricted our models to main sequence stars since the temperature, mass, and radius relations are well defined. For each companion star tested, we found a best fit model.

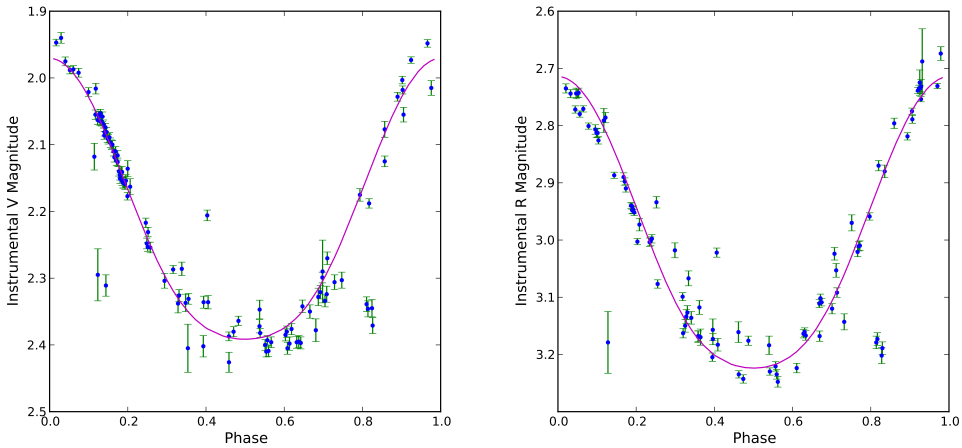

FIG. 6.— These are models and data of HaTr with filters the same as Fig. 5. The companion star in this model is a K2 main sequence star. The parameters used for the CSPN are 83,000K, $0.1R_{\odot}$, aand $0.6M_{\odot}$. The inclination of the system is 45°.

TABLE 2
WORKING PARAMETER SPACE FOR HATR 4 CSPN

Companion Star	T_{comp} (K)	R_{comp} ($R_{\odot}$)	M_{comp} ($M_{\odot}$)	T_{CS}(min) (K)	R_{CS} ($R_{\odot}$)	Inclination
1	5811	1.08	1.16	65,000	0.1-0.55	78-50
2	5486	0.91	0.97	70,000	0.075-0.45	80-45
3	5055	0.75	0.81	70,000	0.05-0.35	82-45
4	4623	0.64	0.65	75,000	0.025-0.3	82-45
5	4212	0.48	0.46	90,000	0.025-0.2	83-50
6	3923	0.38	0.34	90,000	0.025-0.125	85-50

REFERENCES. — Frew (2008)

3.1.1. *Results*

Using our data we revised the orbital period for Sp 1. The revised ephemeris is then

$$T = 2455294.629(10) + 2.9060(15)E.$$

The formal uncertainty on the period is much less than 0.0015 days, however there are several period aliases that we cannot currently distinguish between that are covered by the 0.0015 day uncertainty.

We started modeling in the V filter with eight different spectral types: M5, M0, K5, K2, G8, G2, F8, F2. Since the CS was constrained in temperature, mass and radius, only one working model was found for each companion star. Here we determined that small companion stars would not work because the high inclination needed to have the correct amplitude made the light curve too unlike a sinusoid. G8, G2, F8, and F2 companion stars had the best fits so we made models with G5, G0, and F5 companions. Next we used data from other filters. The B filter did not exclude any model but the R filter excluded G8, G5 and F2. The I filter further excluded G2 and F5 models. The final companions that have working models are the G0 and the F8 stars. The model of the F8 star is shown in figure 3 and G0 in figure 4.

The inclination of the F8 and G0 companion star models are 18° and 19°. Since measuring temperature by the Zanstra method is not very exact, we varied the temperature by about 10%. We changed the radius to keep the luminosity the same and did not change any other parameters other than the inclination. Doing this expanded the range of working inclinations from between 18° and 19° to between 15° and 25°. This agrees with the idea that the system is viewed from almost pole-on as is the nebula.

3.2. *HaTr 4*

The nebula of HaTr 4 has been studied more than the CS. There is not much known about the CS because it is faint. The magnitude is 17.06 in the V filter (Frew 2008). The star was found to be variable by Bond and Livio (1990) with a period of 1.71 days and varies by about 0.4 mag in the V filter. That period did not fit our light curves. We revised the period and arrived at a new ephemeris of

$$T = 2455013.391(5) + 1.73764(4)E.$$

There are no temperature or luminosity measurements in the literature to limit the parameter space of the CS, such as those for Sp 1. Because of that, limiting the parameter space of the CS was a goal of the modeling process.

The nebula is labeled as a possible bipolar since there have been no kinematic studies done to model its shape. Miszalski et al (2009) estimated the inclination to be 45° by the same method as that used for Sp 1. This inclination estimate has the same problems as Sp 1 and is used on as a rough guide. In a more recent preliminary kinematic study, a preliminary value of 85° was reported with a more detailed study underway (Tyndal et al. 2010).

3.2.1. *Results*

As part of the modeling process, we found the maximum and minimum possible values for each parameter.

These ranges depend on the type of the companion star, which was restricted to main sequence as before. For HaTr 4, we input data from V and R filters and fit both filters at the same time. For CS temperature, we started at 50,000K and added 5,000 and tried to find a working model until the minimum temperature is found. We found no upper limit on the temperature other than is physically reasonable. The next parameter we restricted was the radius of the CS. Starting at 0.1 $R_{\odot}$ and increasing at intervals of 0.05 we found the largest radius that did not require a temperature over 200,000 K to fit. We then decreased the radius from 0.1 $R_{\odot}$ at 0.025 intervals to find a minimum. The ranges found are summarized in Table 2. The inclination ranges correspond to the given radius range, such that a larger radius results in a lower inclination.

The inclination was restricted by the light curve shape. Since there is no eclipse in the light curve, the inclination cannot be higher than 80° to 85° depending on the radii of the stars. When the inclination is this high, the curve can be too far from a sine curve to fit the data well. The shape consistently fits well around 75°. As with all the parameters, this value changes slightly depending on the parameters of the companion star. The lower limit depended on when the light curve became too much like a sine curve to fit the data. This limit was around 45° to 50°. Not only was the minimum in the curve not wide enough, the slope did not fit. The light curve of HaTr 4 has a flat bottom. Two models that are near the edges of the inclination curves are shown in figures 5 and 6. These demonstrate the limits of the light curves' shape. These limits on the inclination do not exclude either the 45° or 85° inclination models.

4. CONCLUSIONS

The presented results were determined by comparing the calculated models to the data by eye. This process worked reasonably well however, as the data for both PNe are very scattered making it easy to fit a large range of parameters. Restricting our companion stars to main sequence stars introduces uncertainty in our models. The companion stars will likely be hotter and larger than normal for their mass (De Marco et al. 2008). However, they make a good starting point for later, more rigorous modeling. Since there are at present no complete kinematic models of the Sp 1 or HaTr 4 nebulae, we cannot compare our results with nebular inclination with any certainty. We can say that there are no obvious contradictions with the binary theory at this point in the study.

REFERENCES

Balick, B. & Frank, A. 2002,ARA&A, 40, 439
Bond, H. E., Livio, M. 1990, ApJ, 355, 568
Corradi, R. L. M. & Schwarz, H. E. 1994, A&A, 293, 871
Frank, A., Balick, B., Riley, J. 1990, AJ, 100, 1904
Frew, D. 2008, Planetary Nebulae in the Solar Neighbourhood: Statistics, Distance Scale and Luminosity Function [dissertation], Sydney, Macquarie University.
De Marco, O. 2009, PASP, 121, 316
De Marco, O., Hillwig, T. C., Smith A. J. 2008, AJ., 136, 323
Gray, D.F. 2005, The Observation and Analysis of Stellar Photospheresn (3rd ed.; Combridge: Cambridge University Press)
Miszalski, B., Acker, A., Parker, Q. A., Moffat, A. F. J. 2009, A&A, 505, 249
Mitchell, D. L., Pollacco, D., O'Brien, T.J., Bryce, M., López, J. A., & Meaburn, J. 2006, Planetary Nebulae in our Galaxy and Beyond, 234, 139
Schaub, S.C., Bodman, E.H.L., Hillwig, T.C. 2010, JSARA
Tyndall, A., Jones, D., Lloyd, M., O'Brian, T.J., Pallacco, D.L., & Mitchell, D.L. 2010, Asymmetric Planetary Nebulae 5, published by Ebrary Palo Alto, California, U.S.A., A.A. Zijlstra, I. McDonald & E. Lagadec (eds)