# BINARITY AND INTRINSIC VARIABILITY IN CENTRAL STARS OF PN

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ABSTRACT: 1. Introduction. 2. A list of binary and multiple CSPN. 3. A radial velocity study of CSPN at high spectral resolution. 4. Spectroscopic binaries or intrinsic variables? 5. Concluding remarks.

## 1. INTRODUCTION

We have good reasons to believe that the majority of the stars in the sky are binary or multiple systems (Abt 1983, Poveda et al. 1982). For unevolved binaries (both components at or near the main sequence) the number of binaries per logarithmic interval in P appears to be roughly constant from log P (days) = 0 to 7, with an ill-defined maximum at about 10 years (log P (days) = 3.6); see e.g. Figure 2 of Abt (1983).

Let us briefly consider what is the effect of stellar evolution on this "family" of unevolved binaries. We shall restrict our attention to "intermediate mass stars", i.e. those that become white dwarfs in less than $10^{10}$ years. If we assume that the maximum possible stellar radius is of the order of 1000 solar radii (or about 5 AU), then the separation between binary components that is required to ensure their independent evolution is of about 3000 solar radii (unless the orbit is very eccentric). This limit corresponds roughly to log P (days) = 3.5 - 4.0 for a wide variety of total masses and mass ratios. We can call "wide" and "close" binaries those with separations respectively above and below that limit.

Now we focus our attention on one given star and ask if it is a member of a binary system. If the answer is no, then at the end of its evolution we will have an envelope ejection from a single star, and subsequent transformation into a single white dwarf. If the answer is yes, we ask if the binary is "wide". If yes, we will again have an envelope ejection from a "single" (non-interactive) star. If no, we ask if the binary is "close" enough for coalescence. If yes, we will again have an envelope ejection from a single star. If no, then we will have a case of envelope ejection from a "close" binary system.

Notice that up to now I have avoided the words "planetary nebula". Now we can state our problem with the following two

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questions: (1) do all envelope ejections give rise to detectable planetary nebulae? (2) what is the relative frequency of the two cases of envelope ejection (single vs. close binary)?

I think it is fair to say that we do not have clear answers to these two questions from a theoretical point of view. As a consequence almost any number is conceivable for the percentage of close binaries among central stars of planetary nebulae (CSPN): from a few percent to 100%. Recently Paczynski (1985) presented the most extreme suggestion: perhaps all detectable PN are ejected by close binaries... (this would require a larger birthrate for white dwarfs than for PN).

The purpose of this review is to present the observational evidences about binarity of CSPN. Section 2 gives a list of binary or multiple CSPN (excluding those listed by Bond, see his review in this volume), and also provides several additional comments. Section 3 describes some preliminary results of a radial velocity study of CSPN using high spectral resolution. Several cases of radial velocity variations detected in this survey are discussed in Section 4. Finally, the review is closed with a few inconclusive but optimistic remarks.

## 2. A LIST OF BINARY AND MULTIPLE CSPN

The list in Table 1 is arranged by method of discovery. In the following subsections some additional comments and informations are given.

### 2.1. "Cool" central stars

To notice that the central star is not hot enough to ionize the nebula remains the most effective method of discovering binaries. A cautionary remark is necessary: as we go to later spectral types, the probabilities of misclassification and chance superposition increase. Notice that several of the "cool" CSPN listed by Lutz (1977) have been later reclassified as "not PN" (Acker et al. 1987). In other cases, more detailed studies have not confirmed the presence of a cool central star, or have suggested that it probably is a foreground object (Lutz and Kaler 1983). Another cool object not included in Table 1 is Abell 14 (see Abell 1966). A careful study of this CSPN appears to be lacking.

Unfortunately, to know that a given CSPN is binary is not enough; we would also like to know if it is "wide" or "close". In the case of "cool" CSPN, the very presence of the cool star complicates the investigations. To find that the cool star is a spectroscopic binary is not enough, because the hot star that has ejected and ionized the PN might be a "wide" companion of the spectroscopic binary. On the other hand, consider the visual binary CSPN of NGC 3132: the very faint, hot visual companion of the A-type star might be a close binary... An interesting example of the complications that may arise is given by LT5 (Jasniewicz et al. 1987). The G star appears to be a short period, double-lined spectroscopic binary, implying that a third object is present in the system. But it also seems that the gamma velocity of the double-lined binary is variable, implying that perhaps the hot star is not so far from the short-period binary. To this we may add the light variations, which are not yet well understood. It may require several years of careful work to understand what is happening in the central star of LT5.

Another cool CSPN that deserves additional comments is NGC 2346: it will be mentioned in subsection 2.4.

Cool CSPN have been suggested as a valuable source of reliable distances. Although this is true in a few cases, one has to be careful. It is not a good idea to take the spectral type from the literature, go to Allen's Astrophysical Quantities and extract an absolute magnitude. First we need a reliable determination of Teff and log g for the cool CSPN, using good spectrograms or spectrophotometry and good model atmospheres. This information gives the ratio of luminosity to mass of the cool star. Second, it may be necessary to check if the observed Teff and log g can be obtained using theoretical evolutionary tracks for different masses. If that is the case, there will be more than one possible distance, and it may be impossible to decide which is the correct one. It is good to remember that, spectroscopically, "giant" and "supergiant" mean "low gravity", not necessarily "massive and luminous".

## 2.2. Visual companion of the hot CSPN

The prototype of this method of discovery is the central star of NGC 246. Since the probability of chance superposition is not negligible, we need additional information: for example, proper motions or radial velocities. The paper by Cudworth (1973) gives proper motions for NGC 246 and for some of the pairs he found. It seems that no further work has been made on these objects.

The spectroscopic distance of the 14th magnitude G8 V - K0 V companion in NGC 246 (420 ± 40 pc, Minkowski and Baum 1960) has been traditionally considered one of the best PN distances. It was derived assuming an absolute visual magnitude $M_V = +6.1 \pm 0.2$ for the cool star. Recently, Husfeld (1986, 1987) has obtained a spectroscopic distance for the hot companion: 960 ± 300 pc. In view of this discrepancy, it would be a good idea to study the cool star again. Even if we do not change the spectral classification, according to Allen (1973) a G8 V star can have $M_V = +5.5$, which would give a distance of almost 600 pc. I apologize for using the Allen tables after my remark in section 2.1.

## 2.3. Photometric variations

We have seen that "cool" CSPN are not a very promising source of close binaries. The search for photometric variations has been much more successful. The review by Bond in this volume brings information about 6 close binary CSPN + Abell 35 (which still needs confirmation as a close binary, see Jasniewicz 1987) + 2 cataclysmic variables surrounded by old PN (Krautter et al. 1987, Bode et al. 1987). Bond estimates that about 10 - 15% of all CSPN are binaries with $P < 1$ day.

TABLE 1. A LIST OF BINARY CSPN

1. "Cool" central stars

| OBJECT NAME | SPECTRAL TYPE OF CSPN | HOT STAR? | RAD VEL VARIAB? | PHOTOM VARIAB? | REFERENCES |
|---|---|---|---|---|---|
| IRAS 1912+172P09 | B9 V | not detected | | | 1 |
| NGC 1514 | A | detected | no | no | 2,3,4 |
| NGC 3132 | A2 V | resolved | no | | 5,6,7 |
| He 2-36 | A2 III | not detected | no | | 5,7 |
| NGC 2346 | A5 V | detected | yes | yes | 5,7,8 |
| Cn 1-1 | F5 III-IV | not detected | no | | 9,10 |
| M 1-2 | G2 Ib | not detected | no | no | 11,12,13 |
| LT 5 | G5 III | detected | yes | yes | 14,15 |
| Abell 35 | G8 III-IV | detected | | yes | 16,17 |

2. Visual companion of the hot CSPN

| OBJECT | REFERENCE |
|---|---|
| NGC 246 | 18 |
| NGC 650-1 | 19 |
| Abell 24 | 19 |
| Abell 30 | 19 |
| Abell 33 | 19 |
| NGC 6853 | 19 |

3. Photometric variations

6 close binary CSPN
+ Abell 35
+ 2 cataclysmic variables surrounded by old PN (see review by Bond in this volume)

4. Spectroscopic binaries

| OBJECT | P(days) | REF. |
|---|---|---|
| NGC 2346 | 15.99 | 7,20 |
| NGC 6826 | 0.2377 | 21,22 |
| M 1-67 | 2.4? | 23 |

5. Composite spectrum

The central star of Sp 1 (PK 329 +2 1) (see text and reference 24)

1. Whitelock and Menzies 1986
2. Greenstein 1972
3. Seaton 1980
4. Bond and Grauer 1987
5. Mendez 1978
6. Kohoutek and Laustsen 1977
7. Mendez and Niemela 1981
8. Costero et al. 1986
9. Lutz 1984
10. Bhatt and Mallik 1986
11. O'Dell 1966
12. Feibelman 1983
13. Grauer and Bond 1981
14. Feibelman and Kaler 1983
15. Jasniewicz et al. 1987
16. Jacoby 1981
17. Jasniewicz 1987
18. Minkowski and Baum 1960
19. Cudworth 1973
20. Mendez et al. 1982
21. Noskova 1980
22. Acker et al. 1982
23. Moffat et al. 1982
24. Mendez et al. 1987

### 2.4. Spectroscopic binaries

The list of spectroscopic binaries may look disappointingly short; but notice that a few cases reported earlier have turned out to be false alarms. An outstanding example of false alarm is NGC 1360 (Mendez and Niemela 1977). When I could not confirm the velocity variations on subsequent spectrograms, I thought that perhaps the orbit was very eccentric (Mendez 1980). After several additional and unsuccessful attempts, now I believe that for some unknown reason the old stellar velocities were wrong.

Two comments are necessary about NGC 2346. First, since I have seen its central star described as an eclipsing binary, and this might be misleading, I would like to emphasize that the spectacular light variations discovered by Kohoutek (1982) were not produced by the eclipse of one star by the other, but instead by the slow passage of a dense dust cloud in front of the binary system (Mendez et al. 1982, Costero et al. 1986). If you look now (1987) at the A-type central star (it has received the name V651 Mon) you will find that it has again the constant brightness it showed before the passage of the dust cloud.

The second comment is that it has not yet been possible to check if the companion of the A-type star is really the hot star. As mentioned in 2.1, the system might be multiple, with the hot star as a wide companion of the spectroscopic binary. A few high-resolution spectrograms in the far ultraviolet, where the hot star is detectable, would probably solve the problem.

Concerning NGC 6826, it is obvious that it should be observed photometrically.

M1-67, with its WN8 central star, has been going in and out of the catalogues of PN. The last (and probably definitive) argument to consider it as a PN is by van der Hucht et al. (1985), based on their detection of IR emission from a circumstellar dust shell, with a temperature falling within the range of dust temperatures found to be common in PN (thermal emission by heated dust associated with Pop. I WR stars is quite different). If we accept M1-67 as a PN, then its central star must be included in Table 1, because according to Moffat et al. (1982) it is a spectroscopic binary and it also shows light variations. Of course, since Moffat et al. took it as a Pop. I star, several details in their paper need revision. Besides, given the small amplitudes of their light- and radial velocity curves, additional observations would be very useful.

### 2.5. Composite spectrum

I have added this subsection because of the central star of Sp 1 (PK 329+2 1). Observed at high spectral resolution, its spectrum is a curious mixture of low (30000 K) and high (100000 K) temperature features. Because of space limitations, I cannot give here a detailed description. We (Mendez et al. 1987) believe that Sp 1 is probably a close binary system composed of a very hot star and a cool companion, one of whose hemispheres is heated by radiation from the hot star. Further comments in Section 3.

## 3. A RADIAL VELOCITY STUDY OF CSPN AT HIGH SPECTRAL RESOLUTION

If we want a reliable observational determination of the percentage of close binary CSPN and of their period distribution, then a search for spectroscopic binaries is necessary, because the photometric method is not sensitive to periods longer than a few days. Unfortunately, the search for spectroscopic binaries requires a high spectral resolution. Consider the situation as it was 5 years ago, working at spectral resolutions of a few Å, when it was difficult to detect semiamplitudes of less than 30 Km/s for typical hot CSPNs. We can estimate the maximum detectable orbital period for K1 ≥ 30 Km/s and circular orbits, as a function of the masses M1 and M2 (M1 is the visible star), using

$$P\ (\text{days}) = 9.65\ 10^{6}\ K1^{-3}\ \sin^{3}i\ M2^{3}\ (M1+M2)^{-2} \qquad (1)$$

where all masses are in solar masses. The results are in Table 2, for i = 45° and typical combinations of M1 and M2. Clearly, we need more accuracy if we want to extend the search to significantly longer periods.

TABLE 2

Maximum detectable period MDP (days)
for i=45° and a minimum detectable K1 = 30 Km/s

| M1 | M2 | MDP | log MDP |
|---|---|---|---|
| (solar masses) | | | |
| 0.6 | 0.6 | 19 d | +1.27 |
| 0.6 | 0.3 | 4.2 d | +0.62 |
| 0.6 | 0.15 | 0.75 d | -0.12 |

The situation is much better now. In what follows I would like to present some preliminary results of a search for radial velocity variations in CSPN at a spectral resolution of 0.3 Å. The spectrograms were taken with CASPEC, the Cassegrain echelle spectrograph of the ESO 3.6 m telescope at La Silla, Chile. The selected spectral coverage is from 4000 to 5000 Å, and up to now we have extracted useful information from 62 spectrograms of 28 CSPN with apparent visual magnitudes in the range 10 - 14. A more detailed description of the results is in preparation. Some spectral descriptions can be found in Mendez et al. (1987). Typical exposure times were between 30 and 60 minutes.

A great advantage of these CASPEC spectrograms is that in many cases we can measure the radial velocities of narrow stellar absorptions and emissions of C, N, O and Si, which are much more reliable than the broad H and He lines, and are not contaminated with nebular emissions.

Table 3 shows the nebular velocities, compared with those listed by Schneider et al. (1983), and the differences between stellar and nebular velocities, for 22 CSPN. In several cases we obtained 2 consecutive spectrograms of each CSPN. Since no significant differences were found, in Table 3 the corresponding velocities have been combined (this is indicated with asterisks). The central star of EGB 5 (see Mendez et al. 1987) was not included in Table 3 because there is no information about the nebular velocity of this object. The stellar velocity is +65 and +68 Km/s on two spectrograms taken on consecutive nights. The 5 remaining CSPN will be mentioned in Section 4.

Some details in Table 3 need comment: (1) the redshift shown by the central star of NGC 7293 can be interpreted as gravitational. A more careful determination (the number we give is derived from rather uncertain measurements of the wings of the He II 4686 absorption) would give valuable independent information about the surface gravity and the distance of this CSPN (see Mendez et al. 1987). (2) the radial velocities of the central star of IC 2448 are uncertain, because the spectrograms are noisy and only one stellar line is measurable (C IV 4658 in emission). (3) the stellar He II 4686 often gives discrepant results. We interpret these discrepancies as wind effects. Sometimes we find a redshifted emission (sometimes accompanied by a clearly seen blueshifted absorption). But in some other cases we find a blueshifted emission (e.g. M1-26 and Tc 1). In the cases of H2-1 and He 2-151 we find a redshifted absorption, which may indicate the presence of an incipient blueshifted emission (more details in Mendez et al. 1987). Another case of blueshifted He II 4686 emission has been found by Heber et al. (1987) in the spectrum of LSS 1362. (4) The central star of Sp 1 shows the same radial velocity on two consecutive spectrograms, and there is no difference in radial velocity between the low- and high-temperature features. No nebular lines are present in our spectrograms of this star, and thus the difference Vstar - Vneb is uncertain. For the moment we find no support to our suggestion that the central star of Sp 1 is a close binary. But we still think it probably is, and additional observations are planned.

From Table 3 we conclude that now, given just a few spectrograms, it is quite possible to detect semiamplitudes below 6 Km/s; probably even less when the stellar spectrum shows many sharp lines. Looking at formula (1) and Table 2, we find that now the MDPs are at least 100 times longer. In such conditions, a negative result of a wide search for velocity variations would be almost as informative as a positive result.

## 4. SPECTROSCOPIC BINARIES OR INTRINSIC VARIABLES?

Table 4 gives some information about 5 CSPN that have shown radial velocity variations. The central star of He 2-131 was known to have a

TABLE 3. HELIOCENTRIC RV (Km/s) OF PN AND THEIR CS ON CASPEC SPECTRA

| OBJECT NAME | Vneb (a) | Vneb (b) | NUMBER OF STELLAR LINES USED (c) | Vstar-Vneb (Km/s) (d) | NOTES |
|---|---|---|---|---|---|
| NGC 246 | -46 | | 4 | + 1 | |
| NGC 246 | -46 | | 4 | - 1 | |
| NGC 246 | -46 | | 4 | + 5 | |
| NGC 7293 | -28 | -29 | 2* | +16 | Grav. redshift |
| LSE 125 | | - 6 | 21* | + 1 | |
| NGC 7009 | -47 | -48 | 10* | + 4 | |
| NGC 4361 | +10 | +12 | 5 | + 2 | |
| NGC 4361 | +10 | +11 | 6 | + 1 | |
| NGC 1360 | +42 | +47 | 5 | + 1 | |
| NGC 3242 | + 5 | + 6 | 14* | - 2 | |
| NGC 1535 | - 3 | - 2 | 4 | + 2 | |
| IC 2448 | -24 | -27 | 1 | -12 | |
| IC 2448 | -24 | -26 | 2* | + 1 | |
| NGC 6891 | +42 | +42 | 16* | - 1 | 4686 em redshifted |
| NGC 5882 | +10 | +15 | 4* | - 1 | 4686 em redshifted |
| NGC 6629 | +15 | +13 | 16* | - 1 | 4686 em redshifted |
| IC 4637 | +11 | -10 | 3 | + 9 | |
| PHL 932 (e) | +15 | | 8* | + 3 | |
| He 2-182 | -91 | -87 | 10* | - 1 | |
| M1-26 | - 5 | -24 | 4 | + 5 | 4686 em blueshifted |
| M1-26 | - 5 | -24 | 8* | - 1 | 4686 em blueshifted |
| Tc 1 | -83 | -96 | 15* | + 8 | 4686 em blueshifted |
| He 2-108 | - 8 | - 8 | 20* | + 3 | 4686 em redshifted |
| H2-1 | -20 | -21 | 10* | + 6 | 4686 abs redshifted |
| He 2-162 | +33 | +27 | 29* | + 2 | |
| He 2-151 | -128 | -136 | 39* | - 5 | 4686 abs redshifted |
| Sp 1 | -33 | | 33* | + 7 | |

(a) Schneider et al. 1983. (b) This work.
(c) Asterisks indicate that velocities from 2 consecutive spectrograms were combined to obtain the nebular and stellar values.
(d) We used our determination of Vneb whenever possible.
(e) Vneb = +15 ± 20 Km/s, taken from Arp and Scargle 1967.

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variable spectrum (Mendez and Niemela 1979, Surdej et al. 1982) and the central star of IC 418 was known to show photometric and radial velocity variations (Mendez et al. 1986).

The reality of the variations is out of question, but a reliable interpretation is not yet possible. More spectroscopic and photometric information is necessary. It is possible to interpret these variations both as due to binary motion and to fluctuations in the photospheric outflow velocity and mass loss rate.

In the case of IC 418, which up to now has been the one most ca-

TABLE 4. VARIABLE CSPN

| OBJECT NAME | HELIOC. JD (2440000+) | Vneb (a) | Vneb (b) | Vabs-Vneb (Km/s)(c) | BEHAVIOUR OF THE STELLAR EMISSIONS |
|---|---|---|---|---|---|
| PB 8 | 6210.480 | | +22 | -92 | CONSTANT |
| PB 8 | 6210.533 | | +24 | -89 | |
| PB 8 | 6456.792 | | +23 | -145 | |
| NGC 2392 | 6454.679 | +75 | | -21 | CONSTANT |
| NGC 2392 | 6455.589 | +75 | | + 4 | |
| He 2-138 | 5876.639 | -47 | -46 | - 8 | CONSTANT |
| He 2-138 | 5876.684 | -47 | -40 | - 8 | |
| He 2-138 | 6455.866 | -47 | -36 | +24 | |
| He 2-131 | 6207.656 | - 1 | -12 | +23 | ANTIPHASE (with a few exceptions) |
| He 2-131 | 6207.681 | - 1 | -12 | +27 | |
| He 2-131 | 6454.863 | - 1 | -11 | -43 | |
| IC 418 | 6454.589 | +62 | +63 | +12 | ANTIPHASE |
| IC 418 | 6455.547 | +62 | +63 | -20 | |
| IC 418 | 6455.559 | +62 | +63 | -24 | |
| IC 418 | 6456.613 | +62 | +63 | + 6 | |
| IC 418 | 6457.619 | +62 | +63 | -12 | |

(a) and (b) as in Table 3. (c) The differences between the radial velocities of stellar absorption lines and the nebular velocities. In the case of He 2-138 I have not used lines that show P Cygni profiles.

refully studied (Mendez et al. 1986), we are sure that the orbital motion alone (if present) would not be enough to explain the observed variations: the velocity field near the photosphere must be variable.

An explanation in terms of variable outflow velocity appears to be most likely for PB 8, NGC 2392 and He 2-138, because the stellar emissions do not move. The central star of He 2-138 shows variable P Cygni profiles (Mendez et al. 1987). Binary motion would be more probable for IC 418 and He 2-131, because the stellar emissions move in antiphase with the stellar absorptions -the more positive the absorption velocity, the more negative the stellar emission velocity. However, a variable velocity field might conceivably produce such an antiphase effect; consider e.g. the possible behaviour of the redshifted He II 4686 emission when the outflow velocity changes.

Probably our best case for binarity is He 2-131, because we (Mendez et al. 1987) could not fit the observed H and He stellar absorption profiles with theoretical profiles, implying that perhaps the spectrum is composite. But here we might also think that we were trying to force our model atmosphere method beyond its limit of validity.

In summary, I would not claim that any of the variable objects in Table 4 is a close binary until a well defined and confirmed period is found.

## 5. CONCLUDING REMARKS

The existence of intrinsic variations appears to be well confirmed, at least in a few cases, and this will complicate the search for spectroscopic binaries. At the present time it is too early to suggest a number for the percentage of close binary CSPN. If only one or two of the 28 objects in our CASPEC sample are close binaries, and if their periods turn out to be less than one day, then it will be reasonable to conclude that the period distribution of close binary CSPN shows a precipitous drop at P = 1 day, and that not more than 15% of all CSPN are close binaries, because we are able to probe a much larger range of periods than with the photometric method.

However, we cannot yet rule out a much higher frequency of binaries in our sample. If these additional binaries exist, if some of them have periods > 1 day, and if frequently M2/M1 is small, then the period distribution can be flatter, and the percentage of close binaries can be substantially higher.

That the mass ratio can be frequently small is suggested by the available information about the already known close binary CSPN (see Ritter 1987). Besides, a recent paper by Halbwachs (1987) hints that perhaps many unevolved binaries have very small mass ratios.

In spite of the present uncertainties, it seems clear that we have the tools to make important progress. A careful study of the radial velocities of CSPN at high spectral resolution is likely to produce valuable information about both binarity and the almost unexplored subject of intrinsic variability.

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