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V471 Tauri and SuWt 2: The Exotic Descendants of Triple Systems?

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Abstract. V471 Tauri is a short-period eclipsing binary, and a member of the Hyades. It is composed of a hot DA white dwarf (WD) and a cool main-sequence dK2 companion. *HST* radial velocities of the WD, in combination with the ground-based spectroscopic orbit of the K star, yield dynamical masses of $M_{\rm WD} = 0.84$ and $M_{\rm dK} = 0.93\,M_{\odot}$. During the UV observations we serendipitously detected coronal mass ejections from the K star, passing in front of the WD and appearing as sudden, transient metallic absorption. Eclipse timings show that the active dK star is 18% larger than a main-sequence star of the same mass, an apparent consequence of its extensive starspot coverage. The high $T_{\rm eff}$ and high mass of the WD are paradoxical: the WD is the most massive in the Hyades, but also the youngest. A plausible scenario is that the progenitor system was a triple, with a close inner pair that merged after several $\times 10^8$ yr to produce a single blue straggler. When this star evolved to the AGB phase, it underwent a common-envelope interaction with a distant dK companion, which spiraled down to its present separation and ejected the envelope. The common-envelope efficiency parameter, $\alpha_{\rm CE}$, was of order 0.3–1.0, in good agreement with recent hydrodynamical simulations.

SuWt 2 is a southern-hemisphere planetary nebula (PN) with an unusual ring-shaped morphology. The central star is an eclipsing binary with a period of 4.9 days. Surprisingly, the binary is composed of two main-sequence A-type stars with similar masses of $\sim 2.5\,M_\odot$. We discuss scenarios involving a third companion which ejected and ionizes the PN.

WeBo 1 is a northern PN with a ring morphology remarkably similar to that of SuWt 2. Although we hoped that its central star would shed light on the nature of SuWt 2, it has proven instead to be a late-type barium star!

1. Introduction

In recent years it has become increasingly apparent that stellar systems with higher multiplicity than binaries play a role in producing some of the more exotic stellar objects.

In this paper we will discuss two examples of objects that are difficult to understand unless they are now (or were in the past) triple systems. In the process of exploring their properties, we also discovered a further remarkable (but probably not triple) exotic star inside a planetary nebula.

2. V471 Tauri, the Most Exotic Star in the Hyades

V471 Tauri is a short-period eclipsing binary, consisting of a hot DA white dwarf (WD) and a dK2 main-sequence companion. It is the prototypical post-common-envelope and pre-cataclysmic binary, and is of special importance because it is a member of the Hyades cluster.

Using the *Hubble Space Telescope* and its Goddard High Resolution Spectrograph (GHRS), several of us obtained spectra of V471 Tau at Lyα, in order to determine radial velocities of the WD component. The results of this investigation have now been published (O'Brien, Bond, & Sion 2001), so the discussion here will be brief.

We determined the orbital inclination of the system from the constraints imposed by the duration of total eclipse, and by the spectroscopically measured rotational velocity of the dK component (see O'Brien et al. for details and references). In combination with the ground-based spectroscopic orbit of the dK star, our velocity measurements then yield dynamical masses for the components of $M_{\rm WD} = 0.84$ and $M_{\rm dK} = 0.93\,M_\odot$.

The dK star, constrained to rotate synchronously with the 12.5-hr orbit, is extremely active. The eclipse duration shows that the dK star is 18% larger than a Hyades main-sequence star of the same mass, an apparent consequence of its extensive starspot coverage (i.e., the star is forced to expand in order to continue to radiate the luminosity generated in its core).

On two occasions we serendipitously detected the sudden onset of metallic absorption lines in the GHRS spectra. We attribute these to coronal mass ejections (CMEs) from the K star that pass in front of the WD as seen from the Earth. We estimate that the K star emits some 100-500 CMEs per day, in contrast with the solar rate of about 1-3. Details of the CME observations have been published by Bond et al. (2001).

The high T_{eff} (34,500 K) and high mass of the WD present an evolutionary paradox: the WD is the most massive known in the Hyades, but also the hottest and youngest, in direct conflict with expectation. A plausible scenario is that the progenitor system was a triple, with a close inner pair of main-sequence stars. These stars merged after several $\times 10^8$ yr to produce a single blue straggler of about twice the current turnoff mass. When this star evolved to the AGB phase, it underwent a common-envelope interaction with a distant dK companion, which spiraled down to its present separation, and ejected the envelope.

Based on our observations, we know all of the properties of both the progenitor binary (i.e., the AGB star descended from the merged inner binary, plus the more distant dK companion) and of the current system, except for the mass of the AGB star. This mass can be taken as a free parameter, constrained however to lie between the current cluster turnoff mass of $\sim 2.5\,M_{\odot}$ and twice this value. The results are that the common-envelope efficiency parameter, $\alpha_{\rm CE}$, was of order 0.3–1.0, in good agreement with recent hydrodynamical simulations. Population-synthesis calculations indicate that, if this value of $\alpha_{\rm CE}$ is typical of most common-envelope interactions, then there should be a significant population of close binaries inside planetary nebulae, with orbital periods ranging mostly from 0.3 to 30 days.

3. The Exotic Planetary Nebula SuWt 2

As noted above, a significant fraction of planetary-nebula nuclei (PNNi) is expected to be binaries that have undergone common-envelope interactions.

Photometric techniques are useful in finding binary PNNi through the light variability caused by heating effects on the main-sequence companions of the hot nuclei, and occasionally through actual eclipses. Variability, however, is only useful in finding binary PNNi with periods of up to a few days, since the reflection effect rapidly declines with increasing orbital separation. We urge radial-velocity surveys to find longer-period binaries, in order to provide further constraints on $\alpha_{\rm CE}$. See Bond & Livio (1990), Bond (2000), and references therein for discussions and lists of close binary stars in PNe.

A particularly exotic object is the central star of the PN SuWt 2. The PNN was found by Bond in 1991 to undergo eclipses, but it shows no significant reflection effect. CCD photometric observations collected over the ensuing decade have revealed the period to be 4.91 days. Spectrograms obtained by Pollacco in 2000 showed that the system is a double-lined binary, and remarkably both components are early A-type stars.

The velocity curves show both stars to have nearly identical masses, which are $\sim 2.5\,M_{\odot}$ if the orbital inclination is 90°. Such masses are appropriate for main-sequence stars of the observed spectral types. This unique object presents at least two puzzles. (1) What is the source of ionizing radiation? (2) What star ejected the PN? The first problem is exacerbated by our failure to detect any hot component in a UV spectrum obtained with the *IUE* satellite.

Could one of the A stars be undergoing an FG Sge-like "born-again" episode that has temporarily reduced its effective temperature? In this picture, until recently, this component was hot and was the source of ionization; the PN would now be recombining. However, this scenario seems unlikely since, as noted, our mass determinations indicate that neither star is a highly evolved stellar remnant.

We are therefore forced to consider scenarios in which the system is a triple. We suppose that the third star is a hot object, too faint to be detected with *IUE* but sufficiently luminous in the ultraviolet (perhaps in the recent past) to ionize the nebula. The third star also, presumably, ejected the PN, since there is no obvious way for the pair of A stars to have done so. Whether the third star is simply a distant companion that did not interact with the A stars is unclear, but it seems remarkable that the A-type pair is seen nearly edge-on and that the PN is also viewed almost edge-on, as indicated by its morphology.

4. Ring Nebulae and their Peculiar Nuclei

SuWt 2 indeed has a remarkable morphology, as illustrated in Fig. 1 (left), which is derived from narrow-band CCD images obtained by H.E.B. at the 1.5-m reflector at Cerro Tololo. The PN appears as a very thin circular ring, seen almost edge-on (as deduced from the perfectly elliptical shape as projected onto the sky).

This "wedding-ring" morphology is almost unique among PNe, but it is shared by the northern PN WeBo 1. This object was discovered serendipitously on the Digitized Sky Survey by R. Webbink, as recounted in Bond, Pollacco, & Webbink (2002), and Fig. 1 (right) shows a Kitt Peak 0.9-m CCD image.

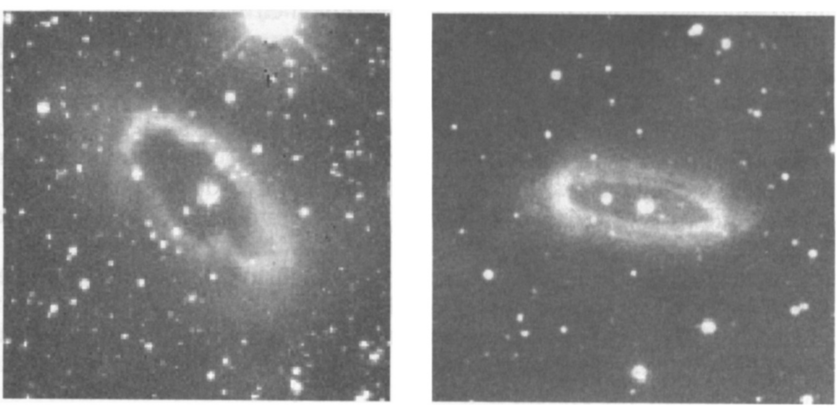

Figure 1. CCD narrow-band images of SuWt 2 *(left)* and WeBo 1 *(right)*, obtained at Cerro Tololo and Kitt Peak, respectively. The images are the sum of frames taken in Hα+[N II] and [O III]. Note the unique ring morphologies of both planetary nebulae.

Pollacco obtained a spectrogram of the central star of WeBo 1 to see whether it would shed light on the nature of SuWt 2. To our surprise, the nucleus of WeBo 1 is also extremely peculiar: it is a red giant with strong spectroscopic features of C_2 and of Ba II and Sr II, which are produced by *s*-process neutron-capture reactions. In other words, it is a classical barium star!

Barium stars were discovered five decades ago by Bidelman & Keenan (1951). The modern view of Ba II stars (see McClure 1984; Jorissen et al. 1998; Bond & Sion 2001) is that they are the binary companions of more massive stars that became asymptotic-giant-branch (AGB) stars, dredged up C and *s*-process elements from their interiors, and transferred them to the companions. The AGB stars have now become optically invisible white dwarfs, leaving the contaminated companions as the visible Ba II stars.

In the case of WeBo 1, the contamination of the visible star must have occurred very recently, and we would expect that UV spectroscopy would reveal a hot PNN companion of the cool star.

In any case, WeBo 1 appears to shed very little light on SuWt 2, except to suggest that the central stars of extreme ring PNe have a strong tendency to be multiple and exotic!

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