Is the Young Star RZ Piscium Consuming Its Own (Planetary) Offspring?

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Abstract

The erratically variable star RZ Piscium (RZ Psc) displays extreme optical dropout events and strikingly large excess infrared emission. To ascertain the evolutionary status of this intriguing star, we obtained observations of RZ Psc with the European Space Agency’s X-ray Multi-Mirror Mission (XMM-Newton), as well as high-resolution optical spectroscopy with the Hamilton Echelle on the Lick Shane 3 m telescope and with HIRES on the Keck I 10 m telescope. The optical spectroscopy data demonstrate that RZ Psc is a pre-main sequence star with an effective temperature of 5600 ± 75 K and log g of 4.35 ± 0.10. The ratio of X-ray to bolometric luminosity, log $L_X/L_{bol}$, lies in the range $-3.7$ to $-3.2$, consistent with ratios typical of young, solar-mass stars, thereby providing strong support for the young star status of RZ Psc. The Li absorption line strength of RZ Psc suggests an age in the range 30–50 Myr, which in turn implies that RZ Psc lies at a distance of $\sim 170$ pc. Adopting this estimated distance, we find the Galactic space velocity of RZ Psc to be similar to the space velocities of stars in young moving groups near the Sun. Optical spectral features indicative of activity and/or circumstellar material are present in our spectra over multiple epochs, which provide evidence for the presence of a significant mass of circumstellar gas associated with RZ Psc. We suggest that the destruction of one or more massive orbiting bodies has recently occurred within 1 au of the star, and we are viewing the aftermath of such an event along the plane of the orbiting debris.

Key words: planet–star interactions – stars: activity – stars: individual (RZ Psc) – stars: pre-main sequence – stars: solar-type – X-rays: stars

1. Introduction

What is the nature of the enigmatic field star RZ Piscium (RZ Psc)? This curious case has been debated for decades (Potravnov et al. 2014b). There exists significant evidence that RZ Psc may be a young main sequence star with a dusty disk that is in the late stages of planet formation (de Wit et al. 2013; Grinin et al. 2015, and references therein). The star’s sharp dropouts in optical magnitude and its large IR excess have prompted the suggestion that a collisionally active asteroid belt is present in orbit around the star (de Wit et al. 2013; Kennedy et al. 2017). Such a scenario is similar to that proposed to explain UX Orionis objects, a class of young stars whose photometric variability is caused by variable circumstellar extinction (Herbst et al. 1994).

Indeed, most age estimates for RZ Psc are based on the assumption that RZ Psc is a UX Ori-type object. The age of RZ Psc was estimated from the equivalent width (EW) of the lithium 6708 Å line as $\sim 10$–$70$ Myr, intermediate between the median ages of stars in the Pleiades and Orion clusters (Grinin et al. 2010). Potravnov & Grinin (2013) estimated an age of $25 \pm 5$ Myr and concluded that the disk orbiting RZ Psc is in transition from primordial disk to debris disk.

However, it is worth considering whether RZ Psc might be an evolved star, given that aperiodic optical dropouts are also observed in such cases (e.g., WD 1145+017; Vanderburg et al. 2015). Indeed, RZ Psc’s high Galactic latitude ($b \approx 35^\circ$) and lack of association with any known young stellar group might suggest evolved star status. If RZ Psc is an evolved giant, its disk may be a consequence of the destruction of a low-mass stellar companion or massive planet when the star expanded to become a red giant. Melis (2009) chose to call such dusty, first ascent giant stars “Phoenix Giants” because of their similarities to T Tauri stars (specifically, high Li abundance and strong infrared excess; Potravnov et al. 2014b).

Furthermore, the strong IR excess associated with RZ Psc ($L_{IR}/L_{bol} \sim 8\%$; de Wit et al. 2013) would be very peculiar if the star is as old as $\sim 25$ Myr. Typically, only cloud-embedded pre-main sequence stars have IR excesses this large (Figure 1 in Mamajek 2009). Many hundreds of young and main sequence solar-type stars have been studied over the past few decades (since the launch of the Infrared Astronomical Satellite), yet few have been found to have $L_{IR}/L_{bol}$ as large as or larger than that of RZ Psc (examples are TYC 8241 2651 1 and V488 Per; Melis et al. 2012; Zuckerman et al. 2012). However, while RZ Psc’s level of IR excess is very unusual for a dusty debris disk, it is quite common for a Phoenix Giant (Zuckerman et al. 2008b; Melis 2009; Melis et al. 2009).

Attempts to distinguish between these evolutionary possibilities—i.e., a young star with a protoplanetary disk versus an evolved star with disk derived from the destruction of a companion—can be quite problematic. X-ray observations may provide key evidence about stellar properties that can break this degeneracy, as has been demonstrated in the case of BP Scutum (Kastner et al. 2010). BP Scutum was initially classified as a classical T Tauri star based on its strong Hα and forbidden line emission (Stephenson 1986), although it is located at high galactic latitude, far from any known star-forming regions.
Zuckerman et al. (2008b) discovered an orbiting, dusty circumstellar disk and a parsec-scale system of highly collimated outflows, which is consistent with the classification of BP Psc as a pre-main sequence star. However, the location of BP Psc in the sky, its weak lithium 6708 Å line, its gravity-sensitive photospheric absorption, the Spitzer Infrared Spectrograph spectrum of highly crystalline submicron-sized dust grains in its circumstellar disk (Melis et al. 2010), and the millimeter-wave molecular spectrum of its circumstellar disk are atypical for pre-main sequence (pre-MS) star–disk systems (Kastner et al. 2008). Chandra X-ray observations of BP Psc revealed that the star is a weak X-ray point source and its X-ray luminosity ratio (log(L_X/L_Bol) ~ ~5.8 to ~4.2) lies in the range that is observed for rapidly rotating (FK Com-type) G stars (Kastner et al. 2010). Hence, the Chandra results favor a scenario wherein the disk/jet system of BP Psc is the result of a very recent engulfment of a companion as the star ascended the giant branch.

To investigate whether the X-ray properties of RZ Psc might similarly discriminate between these potential competing models for its evolutionary state—i.e., young versus evolved star—we have obtained observations of the star with XMM-Newton. To further aid in determining the nature of the RZ Psc system, we obtained optical spectroscopic observations with the Hamilton Echelle on the Lick Shane 3 m telescope and with HIRES on the Keck I 10 m telescope. The observations and data reduction are described in Section 2, the results and analysis are described in Section 3, a discussion of the results is presented in Section 4, and a summary of the results and an outlook for future work is presented in Section 5.

2. Observations

2.1. XMM-Newton European Photon Imaging Cameras (EPIC)

RZ Psc was observed by XMM-Newton (Jansen et al. 2001) for ~38.8 ks on 2015 January 2–3 during revolution 2759. The observations were conducted with the pn, MOS1, and MOS2 CCD arrays of the European Photon Imaging Cameras (EPIC) (Strüder et al. 2001; Turner et al. 2001) operating in full frame mode.

We also obtained simultaneous optical and UV observations with the Optical Monitor available on XMM-Newton. A summary of the XMM-Newton observations and exposure times is listed in Tables 1 and 2. Processing of the raw event data was performed, using standard methods, via the XMM-Newton Science Analysis System (SAS version 14.0).

In Figure 1, we present the merged EPIC pn, MOS1, and MOS2 X-ray images centered near the position of the target star. RZ Psc is the brightest of the few dozen X-ray sources detected in the observation. The associated X-ray source lies at 0°09′42″05, 27°57′01″95′′, coincident with the near-IR position of RZ Psc (Figure 1, right).

2.2. High-resolution Optical Spectroscopy

2.2.1. Lick Shane 3 m Hamilton Echelle

RZ Psc was observed with the Shane 3 m telescope and Hamilton echelle spectrograph (Vogt 1987) at Lick Observatory. The observation dates and parameters are listed in Table 3. Reduction of the Hamilton echelle data was performed using IRAF tasks following the methods outlined in detail in Lick Technical Report No. 74. Briefly, the spectral images were bias-subtracted, flat-fielded, extracted, and finally wavelength-calibrated with ThAr arclamp spectra (see Pakhomov & Zhao 2013).

2.2.2. Keck I 10 m HIRES

RZ Psc was observed with the Keck I 10 m telescope at Maunakea Observatory, where echelle spectroscopy was performed with the HIRES instrument (Vogt et al. 1994). Observation dates and parameters are listed in Table 3. All of the HIRES data were reduced with the MAKEE software package. The spectral images were bias-subtracted and flat-fielded, then the spectra were extracted and finally wavelength-calibrated with ThAr arclamp spectra.

2.3. Keck II 10 m Echellette Spectrograph and Imager (ESI)

A candidate M-type companion to RZ Psc (see Section 3.7) was observed at Maunakea Observatory with the Keck II 10 m telescope. Echelle spectroscopy was performed with the ESI (Sheinis et al. 2002), and observation parameters are given in Table 3. Data were reduced with standard IRAF tasks and procedures similar to the reduction of Hamilton data as described above. Specifically, spectral images were bias-subtracted, flat-fielded with the use of dome flat exposures, extracted, and wavelength-calibrated with the use of CuArXeHgNe arc lamps.

2.4. WIYN 0.9 m Half Degree Imager (HDI)

RZ Psc and its field were observed at Kitt Peak National Observatory with the WIYN 0.9 m telescope<sup>8</sup> in 2016 January. The HDI was used to take 10 s exposures of the RZ Psc field in BVRI filters.

Data were reduced with standard AstroImageJ tasks and procedures (Collins et al. 2017). Multi-aperture differential photometry was then performed to determine the magnitude of stars in the field in all bands.

3. Results and Analysis

In Table 4, we present the key characteristics of RZ Psc that we have gleaned from the literature, and in Table 5, we present the key characteristics determined via the analysis described next.

3.1. Model Atmosphere Analysis

An LTE, 1D model atmosphere analysis of the optical spectra of RZ Psc obtained with the Keck and Shane telescopes was performed using the spectrum synthesis program Moog (Sneden 1973, 2014 version) to determine the atmospheric properties.
parameters and composition of the star. Model atmospheres have been interpolated within the MARCS4 grid (Gustafsson et al. 2008). The line list of Yong et al. (2014) was adopted for atomic data.

Equivalent widths (EWs) were first measured for individual spectra using the splot task in IRAF.\textsuperscript{9} Measurements from different epochs were compared to identify any systematic differences in line strength at different epochs. Since no variations in EWs were found, seven spectra covering a range of dates from 2013 through 2016 were co-added to produce a spectrum of higher S/N; the combined spectrum has an S/N of 200. The combined spectrum with lower noise also reduces the uncertainty in the continuum level, allowing more accurate determination of EWs. The final EWs used for the analysis were measured from the combined spectra.

The first step was to carry out the determination of atmospheric parameters—effective temperature, surface gravity, microturbulence, and metallicity—indepedently of previous determinations. We selected 101 lines of Fe I to cover a range of both line strength and excitation potential, and model atmosphere parameters were varied to minimize the dependence of the derived abundance on EW and excitation potential. The procedure yielded an effective temperature of $5600 \pm 75$ K and a microturbulence of $v_T = (2.0 \pm 0.2)$ km s$^{-1}$. The surface gravity of the star was determined to be $\log g = 4.35 \pm 0.10$ by minimizing the difference in the Fe abundance derived from Fe I and Fe II lines. The resulting metallicity is $[\text{Fe/H}] = -0.11 \pm 0.03$ (standard error of the mean or S.E.M.), not including systematic errors in the atmospheric parameters.

Abundances of additional species were determined once the model atmosphere parameters were established. Again, the Yong et al. (2014) line list provided atomic data. The derived abundances are included in Table 6, along with the estimated uncertainties, including both random and systematic errors, where the solar abundances are taken from Asplund et al. (2009). The uncertainties in the atmospheric parameters are determined from the parameter change needed to establish a clear dependence of abundance versus excitation potential or abundance versus line strength, or a difference in abundance as derived from Fe I and Fe II lines.

Atmospheric parameters for RZ Psc have previously been reported by Kaminkiš et al. (2000) and by Potravnov et al. (2014b). Kaminkiš et al. reported a weighted average temperature of $5250 \pm 50$ K based on their analysis of three spectra with S/Ns in the range 44–68 and a spectral resolving power of $R \approx 25,000$. They employed three alternate methods, including an unreddened color–temperature relation, specific line ratios, and, as we used here, a minimization of the dependence of abundance on the excitation potential for Fe I lines, the “Boltzmann equilibrium.” For this last method, they derived an effective temperature of $5450 \pm 150$ K, which is statistically indistinguishable from our best-fit temperature of $5600 \pm 75$ K. Although their result for microturbulence ($v_T = 2.0 \pm 0.5$ km s$^{-1}$) agrees with ours, their determination of $\log g = 3.41 \pm 0.02$ is discrepant.

Potravnov et al. (2014b) analyzed a higher-resolution spectrum ($R \approx 46,000$) with an S/N of about 75. Their temperature of $5350 \pm 150$ K was obtained from synthetic spectrum fits to a few features, most notably H$\alpha$ and H$\beta$, which may be compromised by circumstellar emission. With the temperature fixed at 5350 K, they used SME analysis software

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\textsuperscript{9} IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.
(Valenti & Piskunov 1996) to determine log $g = 4.2 \pm 0.3$ and $v_T = 1$ km/s.

To attempt to resolve the discrepancies among these model fits, we determined the elemental abundances of RZ Psc using each of the three Kaminski et al. (2000) models with our measured EWs. The Kaminski et al. atmospheric parameters provide a consistent abundance for the Fe I and Fe II lines but significant deficiencies in the abundances of the ionized species Sc II and Ti II. We note that the abundances listed in their Table 3 include large deficiencies of Ti, V, Cr, and Ni, as well as Si and Al.

The Potravnov et al. model atmosphere parameters with our EWs suggest that a value of 2 km s$^{-1}$ for the microturbulence provides a better fit. With that correction, adopting the Potravnov et al. model leads to a significant discrepancy ($\Delta$[Fe/H] = 0.2 dex) between the Fe I and Fe II lines, as well as a low abundance of Fe compared to other metals.

Our adopted model parameters provide both a good match for the Fe I and Fe II lines and a reduced dispersion in the abundances of other species compared to either the Kaminski et al. or the Potravnov et al. models, and we conclude that our adopted model atmosphere parameters provide the best description of the atmosphere of RZ Psc at the epochs of our observations. Our model yields an overall iron abundance [Fe/H] = −0.1 for RZ Psc.

Using the adopted model and the average Li EW of 207 mÅ, we obtain a lithium abundance of A(Li) = 3.05$^{+0.5}_{-1.0}$ for RZ Psc. This analysis uses the Li I line list from Reddy et al. (2002), including a six-component blend of the various explicit features that make up the $^7$Li + $^6$Li feature, and assumes a standard isotopic ratio of 10/1.

### 3.2. Spectral Type

Spectral types ranging from early K to late G have been assigned to RZ Psc in the literature thus far (e.g., Herbig 1960; Kaminski et al. 2000). It appears that RZ Psc is not a main sequence star, given optical spectral diagnostics that are indicative of low surface gravity (Kaminski et al. 2000; Section 3.1). Our determination of an effective temperature of 5600 K and surface gravity of log $g = 4.35 \pm 0.10$ is consistent with a luminosity class of type III/IV. The latter implies that RZ Psc must be either a pre-main sequence star or an evolved star (giant). Adopting this temperature and the empirical spectral type–temperature sequence for 5–30 Myr old pre-main sequence stars presented in Pecaut & Mamajek (2013), RZ Psc appears to have a spectral type of G4 if it is in a pre-main sequence evolutionary stage, but as Herbig (1960) originally noted, the photospheric features of RZ Psc correspond to a later spectral type, K0 IV.

### 3.3. Stellar Activity and Rotation

We examined Lick/Hamilton and Keck/HIRES optical spectra for RZ Psc for indications of stellar activity. Typical features indicative of activity include Hα emission and core-reversal emission in the Ca II H, K, and infrared triplet lines. Figure 2 showcases the dramatic variability displayed by RZ Psc in the Hα region. Variability in the strength of the photospheric absorption component of Hα is evident, as is an additional, presumably circumstellar component that sometimes appears as broad absorption wings around the Hα absorption line core (e.g., 2013 August 14, 2013 October 16, and 2013 November 14; see also Kaminski et al. 2000) or, perhaps, as a stronger core absorption component (2013 November 16; all three spectra for the 2013 November 16 epoch have the same appearance to within their relative S/N). Emission above the continuum level also appears at multiple epochs.

The highly variable Hα line profile of RZ Psc, including the appearance of emission above the stellar continuum, is reminiscent of those of certain young stars that are rotating at near-breakup speeds and are possibly losing mass (e.g., Marcy et al. 1985; Stauffer et al. 1989). However, the $v \sin i$ of RZ Psc (at most 23 km s$^{-1}$; see Table 4) is well below breakup speeds and is otherwise consistent with those of young cluster stars that display similar levels of X-ray activity (e.g., Stauffer et al. 1997, their Figure 6). This suggests a different origin for
Notes.

- Resolution is measured from the FWHM of single arc lines in our comparison spectra.
- S/N measurement is made at 6600 Å in the spectrum.
- Three separate spectra were obtained over the course of the night. The S/N values quoted are for each of the three spectra.

Table 3
Spectroscopic Observations Summary

| Object   | UT Date       | Instrument | Setup               | Coverage (Å) | Resolution $b$ | S/N$^{c}$ |
|----------|---------------|------------|---------------------|--------------|---------------|-----------|
| RZ Psc   | 2013 Aug 14   | Hamilton   | 640 μm slit, Dewar #4 | 3850–6920    | 62,000        | 60        |
| RZ Psc   | 2013 Oct 15   | Hamilton   | 640 μm slit, Dewar #4 | 3850–6920    | 62,000        | 50        |
| RZ Psc   | 2013 Oct 16   | Hamilton   | 640 μm slit, Dewar #4 | 3850–6920    | 62,000        | 50        |
| RZ Psc   | 2013 Oct 21   | HIRES      | Red Collimator      | 4360–8770    | 40,000        | 100       |
| RZ Psc   | 2013 Nov 13   | Hamilton   | 640 μm slit, Dewar #4 | 3850–6920    | 62,000        | 30        |
| RZ Psc   | 2013 Nov 14   | Hamilton   | 640 μm slit, Dewar #4 | 3850–6920    | 62,000        | 35        |
| RZ Psc   | 2013 Nov 16$^a$ | HIRES   | Red Collimator      | 4360–8770    | 100, 65, 40$^a$ | \n
| Notes. |

- $^a$ Resolution is measured from the FWHM of single arc lines in our comparison spectra.
- $^b$ S/N measurement is made at 6600 Å in the spectrum.
- $^c$ Three separate spectra were obtained over the course of the night. The S/N values quoted are for each of the three spectra.

Table 4
Characteristics of RZ Psc from the Literature

| Parameter                | Value | References |
|--------------------------|-------|------------|
| Galactic latitude        | $-35^\circ$ | 1          |
| Proper motion (mas yr$^{-1}$) | 25.4, 11.9 | 1          |
| Proper motion error (mas yr$^{-1}$) | 2.1, 2.0 | 1          |
| $T_{\text{eff}}$ (K)      | 5250  | 2          |
| $\log g$ (cgs)           | 3.41 ± 0.02 | 2          |
| $\sin i$                  | $-0.3 ± 0.05$ | 3          |
| RV (km s$^{-1}$)          | $2 \pm 1.5$ | 4          |
| $v_T$ (km s$^{-1}$)       | $-2.1 ± 0.33$ | 6          |
| $\Delta \lambda$ (Å)     | 202 ± 10 | 7          |
| $L_\lambda/L_{\text{bol}}$ | 0.08  | 4          |
| $M_\odot/M_\odot$        | 1.0   | 8          |
| $L_\lambda/L_{\odot}$    | 0.7   | 8          |
| $M$ (M$_\odot$ yr$^{-1}$) | $\leq 7 \times 10^{-12}$ | 8            |

Note.

$^a$ $[m/H] = \log(N_m/N_H)_{\odot} - \log(N_m/N_H)_{\odot}$ for element $m$ compared to hydrogen; that is, the enhancement or deficiency of an element compared to the Sun.

References. (1) Tycho-2 catalog; (2) Kaminski et al. (2000), (3) Potravnov et al. (2014b), (4) de Wit et al. (2013), (5) Shevchenko et al. (1993), (6) Potravnov et al. (2014a), (7) Grinin et al. (2010), (8) Potravnov et al. (2017).

the circumstellar gas that is responsible for the variable H$\alpha$ emission from RZ Psc; we explore one potential explanation in Section 4.4.
For each Hα emission epoch, we calculated the full width of the double-peaked structures at 10% of the peak line flux. We find that the emission structures have velocity widths \( \lesssim 300 \text{ km s}^{-1} \). Thus, as was concluded by Stauffer et al. (1989) and Marcy et al. (1985) for their rapidly rotating stars, the Hα-emitting material is unlikely to be located at the stellar surface and instead is either being ejected in a wind or is orbiting or infalling within a few stellar radii of RZ Psc.

Steadier emission likely associated with stellar activity is seen in the CaII H and K lines (Figure 3). In some epochs, a blueshifted absorption component is seen adjacent to the emission line, while the UT 2013 November 13 epoch shows a much broader emission line than is seen in other epochs. It should be noted that the spectrum of UT 2013 November 13 is particularly noisy, perhaps as a result of RZ Psc being observed during one of its deep optical minima. The enhanced Hα emission observed during this observation would be consistent with the star being heavily obscured by dust; such behavior is observed, e.g., in the case of the highly inclined for T Cha star/disk system (Schisano et al. 2009). CaII infrared triplet core-reversal emission is evident in the UT 2013 October 21 epoch and some emission is present in the UT 2013 November 16 epoch (Figure 4), although its nature is not immediately obvious given the complex structure in the lines. The high velocity of the emitting material intermittently seen in Hα provides evidence for a wind from (or infall onto) the surface of the star. A similar behavior was observed by Potravnov et al. (2017).

Figure 5 displays the spectral region around the NaI D lines. Clear variability is evident, with blueshifted absorption features regularly appearing and moving away from the photospheric absorption components. Such behavior was noted by Grinin et al. (2015) and served as the basis for their hypothesis that RZ Psc is in the so-called “propeller” regime of mass loss due to a combination of strong magnetic field and low accretion rate.

### 3.4. Radial Velocities

In order to derive RZ Psc’s radial velocity (RV) at each epoch, we cross-correlated each of the HIRES and Hamilton
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Figure 4. Keck HIRES spectra of RZ Psc showing the Ca II infrared triplet complex. Normalization and vertical shifting of spectra is performed as described in the caption to Figure 2. Line variability is evident, with broad absorption components and core-reversal emission. Spectra from 2013 November 16 taken later in the night are consistent with what is shown here to within their respective S/N. Wavelengths in this figure are plotted in vacuum. The wavelength scale of the spectra are not shifted in this figure. The lack of data around 8600 Å is due to the gap between red orders for the HIRES setup used.

Figure 5. Keck HIRES and Lick Hamilton spectra of RZ Psc showing the Na D doublet complex. Normalization and vertical shifting of spectra are performed as described in the caption to Figure 2. Wavelengths in this figure are plotted in vacuum. The wavelength scale for each spectrum is shifted to match the 2013 November 16 epoch for clarity. In each Hamilton spectrum, Na D telluric emission from nearby San Jose, CA, is removed.

spectra with spectra of stars with known radial velocities from Nidever et al. (2002). This process also allowed us to search for any radial velocity variability between epochs. Each of the HIRES and Hamilton spectra yields radial velocity measurements for RZ Psc with a precision of roughly 0.2 km s\(^{-1}\) (Table 7). Excluding the UT 2013 November 13 epoch, there appears to be significantly detected radial velocity variability at the few km s\(^{-1}\) level. This variability appears to be centered on a systemic velocity of roughly $-1$ km s\(^{-1}\), consistent with the radial velocity measurement determined by Potravnov et al. (2014a), and does not have any obvious periodicity. Such measurements seem at odds with the radial velocity of $-11.75 \pm 1.1$ km s\(^{-1}\) measured by Kaminski et al. (2000).

The velocity we determine from the Hamilton spectrum obtained on UT 2013 November 13 appears as a notable outlier when compared to almost all previous radial velocities measured for RZ Psc, apart from the Kaminski et al. (2000) measurement. At this epoch (UT 2013 November 13), the cross-correlation peak splits into two components (Figure 6; i.e., a redshifted absorption line and a weaker blueshifted component). Indeed, when the UT 2013 November 13 spectrum is smoothed, a similar morphology is evident in some absorption lines that is not present in the UT 2013 November 14 spectrum. A deblending fit to the cross-correlation double peak was performed using the FXCOR task within IRAF, and the resulting velocities for each peak (corrected to the heliocentric reference frame) are reported in Table 7. The unusually large negative velocity of the blue peak of the cross-correlation function for 2013 November 13 is marginally consistent with the velocity for RZ Psc determined by Kaminski et al. (2000).\(^{11}\)

3.5. Modeling the X-Ray Spectrum of RZ Psc

Source X-ray spectra were extracted from the XMM pn, MOS1, and MOS2 event lists by selecting photon events within circular regions with diameters of $\sim25''$--$40''$ centered on RZ Psc (Figure 1). Associated background spectra were extracted within circular regions with the same diameters from nearby, source-free regions. We fit the resulting background-subtracted spectra of RZ Psc with the HEASOFT Xanadu\(^{12}\) software package (version 6.16), using XSPEC\(^{13}\) version 12.8.2. The pn, MOS1, and MOS2 X-ray spectra of RZ Psc, displayed in Figure 7, were analyzed using three different models over the range 0.15--10 keV. Each of the adopted models (see below) made use of the XSPEC optically thin thermal plasma model vapec (Foster et al. 2012),\(^{14}\) which is parameterized by plasma elemental abundances, temperature, and emission measure (indirectly, through the model normalization). We included the potential effects of intervening absorption by using XSPEC’s wabs absorption model (Morison & McCammon 1983). All of our models include two temperature components, as required by the $\chi^2$ statistics. The fixed and free parameters for all three models are displayed in Table 8, with the free parameters having associated uncertainty values.

Since the evolutionary status of RZ Psc was unclear to us, we adopted models that were representative of young stars and evolved stars. The first model, hereafter referred to as “T Tauri Star,” uses plasma abundance parameter values that represent average values for T Tauri stars in Taurus (Skinner & Güdel 2013 and references therein); these values are stated in Table 8. For the second model, hereafter referred to as “Evolved Giant Star,” we fixed the parameters for the plasma

\(^{11}\) Unfortunately, it is not clear at which of these epochs (1991 December or 1998 August) Kaminski et al. (2000) obtained this discrepant radial velocity measurement.

\(^{12}\) See http://heasarc.gsfc.nasa.gov/docs/xanadu/xanadu.html.

\(^{13}\) See http://heasarc.gsfc.nasa.gov/xanadu/xspec.

\(^{14}\) See http://www.atomdb.org.
abundances to values that have been determined to be typical for chromospherically active late-type giants (Gondoin 2003a, 2003b, 2003c). In the third model, designated “Free Abundance,” we allowed the abundances of Ne, Fe, and C to be free parameters. Lines of the first two elements likely dominate the emission around the spectrum peak (∼0.3–3 keV) in the relevant (∼10 MK) temperature regime (see, e.g., Kastner et al. 2002). We allowed the abundance of C to be a free parameter in order to fit the spectral feature near 0.3–0.4 keV.

The results of the spectral analysis are presented in Table 7 and Figure 7. Adopting $D = 174$ pc (see Section 4.1), we find a range of X-ray luminosities, $L_X$, from $\sim 5.9 \times 10^{29}$ to $\sim 1.5 \times 10^{30}$ erg s$^{-1}$, depending on the model adopted. The T Tauri and Evolved Giant models yield best-fit values of $L_X$ that are very similar and lie at the lower end of this range. The corresponding range of best-fit $N_H$ values are as small as $\sim 4 \times 10^{20}$ cm$^{-2}$ and as large as $\sim 2 \times 10^{21}$ cm$^{-2}$. The fit results for all three models indicate that the emission measures are similar for both temperature components, with the low- and high-temperature components lying in the ranges $\sim 3$–9 MK and $\sim 10$–20 MK, respectively.

### 3.6. XMM-Newton Optical Monitor Data

The XMM Optical Monitor (OM) photometry was used to determine $UBV$ and $UVM2$ magnitudes of RZ Psc simultaneously with the X-ray measurements. These OM measurements thereby allow us to determine the star’s bolometric flux $F_{bol}$ during the X-ray observations, alleviating uncertainties in determining $L_X / L_{bol}$ that could arise due to the significant optical variability and likely X-ray variability of RZ Psc. The OM photometry is provided in Table 2. It is evident that the star’s flux remained constant in all four passbands during the observations. Based on the $V$-band magnitude obtained with the OM, we further conclude that, during our XMM observations, RZ Psc was not undergoing one of its rare, deep visual minima, which can be as dim as $V \sim 14$ (de Wit et al. 2013). Adopting the mean $V$-band magnitude obtained from the OM photometry and assuming bolometric corrections based on the adopted effective temperature and luminosity class of RZ Psc (see Section 3.2), we obtain $F_{bol}$ values that range from $\sim 6.7 \times 10^{-10}$ to $\sim 6.9 \times 10^{-10}$ erg s$^{-1}$ cm$^{-2}$. Adopting a distance of $170$ pc to RZ Psc (see Section 4.1), we obtain a bolometric luminosity $L_{bol} \sim 0.6 L_\odot$ (excluding any contribution from circumstellar dust).

From the OM photometric results and the adopted effective temperature, which implies $(B-V)_0 = 0.66$, we estimate the optical extinction of this system at the time of our XMM-Newton observations to be $A_V \sim 0.66$ (assuming $R = 3.09$; Rieke & Lebofsky 1985). Our estimated value of $A_V$ is larger than the value of $0.3 \pm 0.05$ quoted in Potravnov et al. (2017). The discrepancy between these values of $A_V$ are consistent with the optical dropout behavior associated with RZ Psc.

### 3.7. Search for Comoving Low-mass Stellar Companions

The high galactic latitude of RZ Psc (see Table 4) and its large displacement from any known nearby young moving group (see Table 1 of Mamajek 2016) are problematic for a young star scenario. Thus, we used the pipeline-generated X-ray source list compiled from the XMM-Newton observation as the basis for a search for young, X-ray active stars that are comoving with RZ Psc. The XMM-Newton images were matched to images from the WIYN 0.9 m telescope and the 2MASS and WISE image archives to identify optical and IR sources coincident with (i.e., within $2\arcsec$ of) those XMM X-ray sources lying within approximately $15\arcsec$ of RZ Psc. This yielded seven X-ray sources.
with optical/IR counterparts, which we regarded as candidate comoving stars. Spectral energy distributions (SEDs) for these seven sources were produced using magnitudes obtained from the WIYN 0.9 m images, along with those available in the 2MASS and WISE catalogs. The resulting SEDs were then fit with stellar atmosphere models\(^\text{15}\) (Castelli & Kurucz 2003). This SED analysis and comparison of the proper motion of

\(\text{15}\) The stellar atmosphere models were obtained from the Castelli and Kurucz grids of model atmospheres: http://kurucz.harvard.edu/grids.html.
Table 8
RZ Psc Model Parameters

| Parameter | Free Abundance | T Tauri Star | Evolved Giant Star |
|-----------|----------------|--------------|--------------------|
| \( N_H \times 10^{21} \text{ cm}^{-2} \) | 1.8 ± 0.5 | 0.564 ± 0.008 | 0.390 ± 0.006 |
| \( kT_1 \) (keV) | 0.97 ± 0.04 | 0.67 ± 0.05 | 0.75 ± 0.04 |
| He | 1.0 | 1.0 | 0.3 |
| C | 66.6 ± 31.3 | 0.45 | 0.3 |
| N | 1.0 | 0.79 | 0.3 |
| O | 1.0 | 0.43 | 0.3 |
| Ne | 0.7 ± 1.4 | 0.83 | 1.0 |
| Mg | 1.0 | 0.26 | 0.3 |
| Al | 1.0 | 0.50 | 0.3 |
| Si | 1.0 | 0.31 | 0.3 |
| S | 1.0 | 0.42 | 0.3 |
| Ar | 1.0 | 0.55 | 0.3 |
| Ca | 1.0 | 0.195 | 0.3 |
| Fe | 0.9 ± 0.3 | 0.195 | 0.3 |
| Ne | 1.0 | 0.195 | 0.3 |
| \( \times 10^{-5} \) | | | |

For RZ Psc, we have conducted an H–R diagram analysis with theoretical pre-main sequence isochrones to estimate the likely range of luminosity of RZ Psc. Following our Li EW analysis, we assume an age range of 30–50 Myr for RZ Psc. The resulting H–R diagram is displayed in Figure 8, where the isochrones and pre-main sequence tracks overlaid are obtained from PARSEC\(^{16}\) (the Padova and Trieste Stellar Evolution Code; Bressan et al. 2012). Figure 8 suggests that RZ Psc is a pre-main sequence star of mass 0.75–1.0 \( M_\odot \). Our H–R diagram analysis yields log(\( L_\odot / L_{bol} \)) in the range of −0.08 to −0.21, which corresponds to a distance to RZ Psc of \( \approx 186 \) pc if RZ Psc is 30 Myr old and to a distance of \( \approx 161 \) pc if RZ Psc is 50 Myr old. This estimated distance range, obtained from our Li- and X-ray-based age range, agrees with the distance estimate of 160 pc mentioned in (Potratz et al. 2017, and references therein). Our age and mass estimates are also consistent with the values cited by those authors (25 ± 5 Myr and 1 \( M_\odot \), respectively).

\(^{16}\) http://stev.oapd.inaf.it/cgi-bin/cmd
Table 9

| Parameter                          | Free Abundance | T Tauri Star | Evolved Giant Star |
|-----------------------------------|----------------|--------------|--------------------|
| \(N_H (\times 10^{19} \text{ cm}^{-2})\) | 18.0 (5.0)      | 5.64 (0.08)    | 3.90 (0.06)        |
| \(kT_1 (\text{keV})\)           | 0.27 (0.05)     | 0.67 (0.05)    | 0.75 (0.04)        |
| \(T_1 (\text{MK})\)             | 3.2 (0.6)           | 7.7 (0.5)         | 8.8 (0.4)          |
| \(kT_2 (\text{keV})\)           | 0.97 (0.04)     | 1.14 (0.08)    | 1.6 (0.1)          |
| \(T_2 (\text{MK})\)             | 11.2 (0.4)      | 13.3 (0.9)     | 19.1 (1.7)         |
| Normalization\(_1\) (\times 10^{-5}) | 4.0 (1.0)       | 7.62 (0.09)     | 6.91 (0.07)        |
| \(EM_1 (\times 10^{52} \text{ cm}^{-3})\) | 2.722            | 5.253          | 4.765              |
| Normalization\(_2\) (\times 10^{-5}) | 3.5 (1.0)       | 6.8 (1.0)       | 6.63 (0.08)        |
| \(EM_2 (\times 10^{52} \text{ cm}^{-3})\) | 2.414            | 4.658          | 4.567              |
| \(\chi^2_{\text{red}}\)         | 1.053           | 1.120          | 1.298              |
| d.o.f.                            | 118             | 121            | 121                |
| Observed flux (\times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}) | 1.262           | 1.269          | 1.301              |
| Intrinsic flux (\times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}) | 4.152           | 1.616          | 1.653              |
| \(L_X (\times 10^{39} \left(\frac{D}{10^3 \text{pc}}\right)^2 \text{ erg s}^{-1})\) | 2.862            | 1.114          | 1.139              |

\[
\log\left(\frac{L_X}{L_{\text{bol}}}\right)\quad (-3.230, -3.294)\quad (-3.640, -3.704)\quad (-3.630, -3.694)
\]

Figure 8. H–R diagram position of RZ Psc, assuming an age range of 30–50 Myr, as shown by the vertical line, overlaid with PARSEC pre-main sequence isochrones and pre-main sequence tracks for a variety of masses (Bressan et al. 2012).

Finally, we consider the UVW velocities of RZ Psc. Adopting a median estimated distance of 170 pc, the Table 4 proper motion, and a median radial velocity of \(-2\ \text{km s}^{-1}\) (Table 7), the UVW velocities are \(-13.4, -18.2, -5.4\ \text{km s}^{-1}\). These UVW values are consistent with young star status—the closest kinematic matches being the TW Hya Association, \(\beta\) Pic moving group, and the Columba Association (Mamajek 2016). However, RZ Psc is much farther from Earth than established members of these groups.

4.2. X-Ray Absorption versus Optical Extinction

In Figure 9, we compare the range of the gas column density we determine from the photoelectric absorption of the X-rays emitted by RZ Psc, \(N_H \sim (0.4–1.8) \times 10^{21} \text{ cm}^{-2}\) (Section 3.5), with the estimate of visual extinction due to dust (\(A_V\)) along the line of sight to the star afforded by the simultaneous XMM-Newton OM data (Section 3.6).

These measurements for RZ Psc are overlaid over empirical \(N_H\) versus \(A_V\) curves for the local ISM and the \(\rho\) Ophiuchi molecular cloud. The figure demonstrates that the relation between absorption and extinction toward RZ Psc is consistent with that of the ISM if we adopt the “Free Abundance” model, i.e., the model results in an \(N_H\) that is most consistent with an \(A_V\) given ISM-like grains. Adopting either of the other X-ray spectral models would imply that the gas-to-dust ratio of the circumstellar material may differ significantly from that of the ISM or \(\rho\) Oph. Such an interpretation of Figure 9 is subject to the important caveat that, because the OM V photometry indicates that RZ Psc was observed in a relatively low-extinction state, we cannot ascertain whether the observed relationship between \(N_H\) and \(A_V\) toward RZ Psc at the time of our observations was representative of the intervening ISM or of the circumstellar material associated with RZ Psc itself.

\[\text{http://kinematics.bdnyc.org/query}\]
4.3. The Puzzling Radial Velocity Behavior of RZ Psc

In our radial velocity (RV) cross-correlation analysis, we find marginal evidence for RV variability, including one epoch in which the cross-correlation function appears double peaked (Figure 6). One possibility that could account for this potential RV variability is that RZ Psc may reside in a spectroscopic binary system, one that can, on rare occasions, be double lined. This would make RZ Psc superficially similar to BD+20 307, which also has a large value of $L_{\text{IR}}/L_{\text{bol}}$, thought to be the result of a catastrophic collision of terrestrial mass planets (Zuckerman et al. 2008a).

If RZ Psc is indeed a spectroscopic binary, then there would be a new, interesting route through which we could explore the age and evolutionary status of the system. If both stars are main sequence, then both should have comparably strong lithium absorption. We examined the line shape of the UT 2013 November 13 Li I λ6708 line to see if it shows a blueshifted shoulder. First, the EW of the Li I line was measured in all epochs. To within the uncertainties of each epoch, these EWs agreed. Next, a smoothed Li I line was compared to other comparatively strong lines at similar wavelengths, most notably the Ca I λ6717 line. While the Ca I line showed an obvious slightly weaker blueshifted shoulder, the Li I line did not. Finally, cross-correlations were performed between the UT 2013 November 13 spectrum of RZ Psc and other stars using only single lines. Most single lines showed either double-peaked cross-correlation maximums or significant broadening in the blueshifted region where the second peak would be expected. The Li I line, in contrast, was well fit with a single Gaussian and showed no signs of blueshifted broadening. The velocity of the Li I line, however, does not match either velocity measured on UT 2013 November 13 via cross-correlation analysis but rather lies in between these two velocity signals. This complication makes it difficult to interpret Li I as present in only one star in a putative binary system.

4.4. What is the Origin of the Circumstellar Material Orbiting RZ Psc?

The extreme dropout events in the optical light curve of RZ Psc invite comparisons between this system and objects showing similarly dramatic dropouts, such as the variable field star KIC 8462852 (aka “Tabby’s Star”; Boyajian et al. 2016) and the remarkable “polluted” white dwarf WD 1145+017 (e.g., Rappaport et al. 2016). The profound, seemingly aperiodic, variability observed in both of those cases has been cited as evidence for the presence of orbiting and/or infalling circumstellar debris arising either from a catastrophic collision or tidal stripping of a subplanetary-mass body or bodies. Xu et al. (2016) suggest that the atomic absorption lines observed in the spectrum of WD 1145+017 could come from either a burst of accretion due to disintegrating planetesimals, a previous tidal disruption, or both.

As in the case of WD 1145+017, which displays wide and variable gaseous absorption lines in its spectrum that are indicative of a gas-rich disk (Xu et al. 2016), the presence of rapidly variable emission and absorption in the wings of RZ Psc’s H α line profiles (Figure 2) suggests that its orbiting debris includes a significant gaseous component. However, in terms of evolutionary state and, hence, the nature of the disrupted orbiting body or bodies, the (G-type) RZ Psc system would appear to have more in common with (F-type) KIC 8462852 than WD 1145+017. Indeed, a major difference between the RZ Psc and KIC 8462852 systems would appear to be that the circumstellar mass associated with RZ Psc is far larger than that associated with KIC 8462852. Specifically, unlike RZ Psc, KIC 8462852 does not have a detectable IR excess, and its optical dropouts are far less pronounced; whereas RZ Psc suddenly dims by several magnitudes (de Wit et al. 2013), the sudden dips in flux exhibited by KIC 8462852 are of the order of ~20% or less (Boyajian et al. 2016). This suggests that the putative body (or bodies) destroyed around RZ Psc was far more massive than in the case of the KIC 8462852 system, whose debris has variously been attributed to a rocky body originally a few hundred kilometers in diameter with a mass of at most $10^{-6}$ Earth masses (Boyajian et al. 2016) or to a handful of disintegrating cometary bodies (Neslušan & Budaj 2017).

We hence propose that the puzzling variability behavior and enormous infrared excess of RZ Psc is most readily ascribed to the aftermath of the recent tidal disruption of a substellar companion or giant planet, or a catastrophic collision involving one or more relatively massive, gas-rich orbiting bodies. Evidently, as in the cases of KIC 8462852 and WD 1145+017, the enormous dips in the optical light curve of RZ Psc require that the orbiting debris resulting from this destructive event is confined to a disk that lies nearly along our line of sight to the star. Although the bulk of the dusty debris is likely orbiting ~0.3 au from the star (based on the temperature of the dust excess, ~500 K; de Wit et al. 2013), the broad absorption features in the H α line profiles of RZ Psc indicate that at least some of the circumstellar material is either accreting onto the star, outflowing, or both.

Although the preponderance of evidence appears to support the young star status of RZ Psc, there are some caveats to be considered. The consumption of a giant planet or substellar companion could be polluting the atmosphere of RZ Psc, thereby increasing the atmospheric abundance of Li, which would make the star appear younger than it is (see, e.g., Sandquist et al. 2002). Our measured (relatively low) value of log g could similarly be explained by the accretion of debris from a substellar-mass companion, given that the primary would be expected to expand during the accretion process. Indeed, it is possible that log g may be variable as a consequence of this (presumably ongoing) planet or substellar companion consumption process. Accretion of material from a disrupted massive body would also increase the magnetic activity of the star, and hence might also explain the prodigious X-ray output of RZ Psc. Thus, we should look to Gaia’s forthcoming determination of the parallax distance and refinement of the space velocity of RZ Psc as the primary means to verify its youth.

5. Summary and Conclusions

We used XMM-Newton, along with high-resolution optical spectroscopy, to characterize the properties of the infrared-excess, variable star RZ Psc so as to confirm its evolutionary status. The XMM-Newton observations produced a detection of a bright X-ray point source coincident with the centroids of the optical and infrared emission at RZ Psc, with the log of the ratio of X-ray to bolometric luminosity, $\log L_{\text{x}}/L_{\text{bol}}$, in the range $-3.7$ to $-3.2$. These results are consistent with the $\log L_{\text{x}}/L_{\text{bol}}$ ratios typical of low-mass, pre-main sequence
stars, and larger than that of all but the most X-ray-active stars among giants (e.g., FK Com-type giants). Examination of the X-ray sources in the RZ Psc field yields one candidate comoving (M dwarf) star, but the radial velocity of this potential wide (2/3 separation) companion is inconsistent with that of RZ Psc.

High-resolution optical spectra obtained with the Hamilton Echelle on the Lick Shane 3 m telescope and with HIRES on the Keck I 10 m telescope indicate that RZ Psc has an effective temperature and a surface gravity that are consistent with a pre-main sequence star. Sporadic radial velocity variability may also be observed in RZ Psc; if confirmed, this would suggest that it may be a spectroscopic binary system. We note that the potential radial velocity variability and bizarre Hα emission-line profile variability observed for RZ Psc are both reminiscent of the 5–10 Myr old star T Cha, which also exhibits deep absorption episodes, like RZ Psc, due to an inclined dusty disk (Schisano et al. 2009).

The XMM-Newton and high-resolution optical spectroscopy results favor a young star status for RZ Psc. Measurements of the Li EW indicate that RZ Psc is a ∼30–50 Myr old post-T Tauri star. If the age of RZ Psc is indeed this advanced, the presence of significant, varying column densities of circumstellar gas and dust renders it extremely unusual among Sun-like pre-MS stars. By analogy with objects such as KIC 8462852 (a.k.a. “Tabby’s Star”; Boyajian et al. 2016) and WD 1145+017 (e.g., Rappaport et al. 2016), it is possible that, in the RZ Psc system, we are seeing evidence of a catastrophic event, for example, the destruction of a massive planet. Optical spectral features indicative of activity and/or circumstellar material, such as core-reversal emission in the Ca II H, K, and infrared triplet lines and Hα emission, are present in our spectra over multiple epochs and provide evidence for the presence of a significant mass of circumstellar gas associated with RZ Psc. The presence of a significant mass of circumstellar gas (as reflected in the broad Hα emission-line profiles) might imply that the cannibalized planet was a hot Jupiter.

An H–R diagram analysis indicates a distance to RZ Psc of ∼170 pc if RZ Psc is a pre-main sequence star. Gaia should provide the parallax distance and space velocity measurements necessary to nail down the evolutionary status of RZ Psc and to refine estimates of its age. Further observations are warranted to understand the nature of this enigmatic star: high-resolution X-ray spectroscopy of RZ Psc would improve constraints on the abundances of RZ Psc’s X-ray-emitting plasma; an optical and infrared spectroscopy campaign would shed light on the potential binary nature of the system; and submillimeter interferometer imaging and optical/IR coronographic adaptive optics imaging would establish whether there is cold, extended gas and dust associated with the RZ Psc disk.

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