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Abundance analysis of the recurrent nova RS Ophiuchi (2006 outburst)

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HIGHLIGHTS

- We analyze elemental abundances of RS Oph (2006) using CLOUDY.
- Model generated spectra are matched with observed optical and NIR spectra.
- The best fit model parameters are obtained using chi square technique.
- We find enhanced abundance, relative to solar, of He, N, Ne, Fe and Ar.
- Estimated ejecta mass $\sim 4 \times 10^{(-6)}$ Msun which is consistent with other results.

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ABSTRACT

We present an analysis of elemental abundances of ejecta of the recurrent nova RS Oph using published optical and near-infrared spectra during the 2006 outburst. We use the CLOUDY photoionization code to generate synthetic spectra by varying several parameters, the model generated spectra are then matched with the observed emission line spectra obtained at two epochs. We obtain the best fit model parameters through the χ^2 minimization technique. Our model results fit well with observed optical and near-infrared spectra. The best-fit model parameters are compatible with a hot white dwarf source with T_{BB} of $5.5–5.8 \times 10^5$ K and roughly constant a luminosity of $6–8 \times 10^{36}$ ergs s^{-1}. From the analysis we find the following abundances (by number) of elements with respect to solar: $He/H = 1.8 \pm 0.1$, $N/H = 12.0 \pm 1.0$, $O/H = 1.0 \pm 0.4$, $Ne/H = 1.5 \pm 0.1$, $Si/H = 0.4 \pm 0.1$, $Fe/H = 3.2 \pm 0.2$, $Ar/H = 5.1 \pm 0.1$, and $Al/H = 1.0 \pm 0.1$, all other elements were set at the solar abundance. This shows the ejecta are significantly enhanced, relative to solar, in helium, nitrogen, neon, iron and argon. Using the obtained parameter values, we estimate an ejected mass in the range of $3.4–4.9 \times 10^{-6}$ $M_\odot$ which is consistent with observational results.

1. Introduction

RS Ophiuchi (RS Oph) is a well-observed recurrent nova (recurrence period ~20 years) and is one of the ten confirmed recurrent novae that belong to our galaxy (Kato and Hachisu, 2012; Schaefer, 2010). The RS Oph system is composed of a massive (~ 1.35 $M_\odot$, Kato et al., 2008) white dwarf (WD) primary accompanied by a red giant secondary of estimated spectral class around M2 III (Worters et al., 2007 and references therein). Brandi et al., 2009 estimated the orbital period to be 453.6 days, the red giant mass, $M_g = 0.68–0.80$ $M_\odot$ and the orbital inclination, $i = 49^\circ–52^\circ$ for the system. The outburst takes place due to a thermonuclear runaway (TNR) on the WD surface that accretes matter from the secondary red giant companion. The outburst causes ejection of mass $\sim 10^{-6}–10^{-8}$ $M_\odot$ at a high speed of ~4000 km s^{-1} (e.g. Buil, 2006). Previous studies of outbursts indicate that the WD mass of RS Oph is possibly increasing due to the accumulation of a percentage of the accreted matter on its surface. Consequently, the mass of the WD in RS Oph may gradually reach the Chandrasekhar limit and explode as a Type Ia supernova – this has made RS Oph an object of great significance to the astrophysicists. However, there have been considerable debates about this hypothesis (Starrfield et al., 2004; Wood-vasey and Sokoloski, 2006).

RS Oph was detected in outburst previously in 1898, 1933, 1958, 1967, 1985; its latest outburst was discovered on 2006 February 12.83 UT (Hirosawa, 2006). The reason for the much shorter recurrence period in the RS Oph system, in comparison to classical novae (CNe), is due to combined effect of the high WD mass and a high accretion rate (Starrfield et al., 1985; Yaron et al., 2005). The two recent outbursts of RS Oph in 1985 and

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2006 have been observed intensively over a wide range of wavelengths, from X-rays to the radio regions (Bode, 1987; Evans et al., 2008). Detailed studies display very similar characteristics of the outbursts. In the early phase of the outburst, the spectra show broad, low-ionization emission features of H, He, N, O and Fe; the nova enters quickly (about a month after outburst) to the nebular phase with the emergence of strong coronal (e. g., [Fe XIV] 0.5303 μm, [Ar X] 0.5535 μm, [Fe X] 0.6374 μm, [Si VI] 1.9641 μm, [Al IX] 2.0444 μm, [Mn XIV] 2.0894 μm) and nebular lines (e.g., [O III] (0.4363, 0.4959 and 0.5007 μm) and [N II] 0.5755 μm) (Iijima, 2009; Banerjee et al., 2009). The nova light curves also behave similarly; they decline fast with $t_2 \sim 6$ and $t_3 \sim 17$ days (Rosino, 1987; Munari et al., 2007). The key result of the 1985 and 2006 observations was the detection of a shock that is generated while the ejecta interacts with the surrounding wind of the red giant secondary (Bode and Kahn, 1985; Das et al., 2006 and references therein) and a non-spherical bi-polar shape of the nova ejecta (e.g., Taylor et al., 1989; Chesneau et al., 2007; Bode et al., 2007). Further investigations also helped to determine a few important parameters viz. determinations of the distance, d = 1.6 ± 0.3 kpc (Hjellming et al., 1986), the interstellar hydrogen column density, $N \sim 2.4 \times 10^{21}$ cm^{-2} (Hjellming et al., 1986), and an interstellar reddening of $E(B-V) = 0.73$ (Snijders, 1987).

However, despite plenty of observations of RS Oph, the abundance analysis of the nova ejecta has not been done adequately. A few values have been calculated, for example, from optical studies of the 1985 outburst, Anupama and Prabhu (1989) derived a helium abundance of $n(He)/n(H) = 0.16$; Evans et al., 2007 estimated the O/Ne ratio (by number) to be $\gtrsim 0.6$ from IR studies of the 2006 outburst. A complete knowledge of elemental abundances in the ejecta is of crucial importance for several reasons, for example, to understand the TNR process that leads to the nova explosion, the composition of material of the WD, as there is a possibility of mixing of WD material with the ejecta, the contribution of novae to the chemical evolution of galaxy etc. In this paper, we report the results of an elemental abundance analysis of the ejecta of RS Oph by modeling its available optical and near-infrared (NIR) spectra observed during the 2006 eruption. We have used the photoionization code CLOUDY (version 13.02; Ferland et al., 2013) to generate spectra, by varying the parameter values. Model generated spectra are then compared with the observed emission line spectra, the best fit model is chosen by calculating the corresponding χ^2 values. The procedure of modeling is described in Section 3; results obtained from the analysis is described in Section 4.

2. Photoionization model analysis

We use the CLOUDY photoionization code, C13.02 (Ferland et al., 2013) for the abundance analysis in RS Oph. The benefit of using photoioinization models is that in addition to elemental abundances, they also provide estimate of several other parameters, e.g., density, source luminosity, source temperature etc. Previously, this method was used to determine the elemental analysis and physical characteristics of a few novae by modeling the observed spectra, for example, LMC 1991 (Schwarz et al., 2001), QU Vul (Schwarz, 2002), V1974 Cyg (Vanlandingham et al., 2005), V838 Her & V4160 Sgr (Schwarz et al., 2007a), V1186 Sco (Schwarz et al., 2007b), V1065 Cen (Helton et al., 2010). The photoionization code CLOUDY uses a set of parameters that specify the initial physical conditions of the source and the ejected shell. The source is described by the spectral energy distribution of the continuum source, its temperature and luminosity. The physical condition of the shell is described by the density, inner and outer radii, geometry, covering factor (fraction of 4π sr enclosed by the model shell), filling factor (ratio of the contribution of the dense shell to the diffuse shell) and elemental abundances (relative to solar). The density of the shell is set by a hydrogen density parameter and the elemental abundances, relative to hydrogen, are set by the abundance parameters. The hydrogen density, $n(r)$, and filling factor, $f(r)$, may vary with the radius as given by the following relations,

$$n(r) = n(r_0)(r/r_0)^{\alpha}\ \mathrm{cm}^{-3} \quad \& \quad f(r) = f(r_0)(r/r_0)^{\beta} \tag{1}$$

where, r_o is the inner radius, α and β are exponents of power laws. We choose $\alpha = -3$, the filling factor = 0.1 and the filling factor power-law exponent, $(\beta) = 0$, which are the typical values used in similar kind of studies (e.g., Schwarz, 2002; Vanlandingham et al., 2005; Helton et al., 2010).

CLOUDY solves the equations of thermal and statistical equilibrium using the above mentioned set of input parameters to generate output spectra from the non-LTE ejecta illuminated by the central source. Its calculations incorporate effects of important ionization processes, e.g., photo, Auger, collisional and charge transfer and recombination process viz. radiative, dielectronic, three-body recombination, and charge transfer. We assume the continuum shape to be a blackbody of a high temperature $T_{BB} \geqslant 10^5$ K, as done in the previous investigations, to ensure that it supplies the correct amount of photons for photoionization. The output predicts the flux of emission lines, which is compared to the measured line fluxes in the observed spectra.

3. Modeling procedure

For the present analysis, we use observed optical and NIR *JHK* spectra of the 2006 outburst of RS Oph. Modeling of both optical and NIR data enables to sample over a broader range of ionization and excitation levels in the emission lines and thus helps to constrain the results more accurately. We choose two epochs of observations taken at different times of the nova evolution, that had nearly simultaneous optical and NIR spectra and form two data sets represented by D31 and D49. D31 consists of optical and NIR spectra that is observed, respectively, on 2006 March 15 and March 16 i.e. approximately 31 days after outburst; whereas, D49 consists of optical and NIR spectra observed, respectively, on 2006 April 4 and April 2, i.e. approximately 49 days after outburst. Here, for simplicity, we assume that the physical condition and corresponding parameters, in the ejecta remain unchanged over 1–2 days. Details about the used spectra are presented in Table 1. A detailed modeling using more data sets extended over a larger time period and including other wavelength regions is in progress and will be published later.

We assume a spherically symmetric expanding shell geometry of the ejecta that is illuminated by the central source. Several spectra are generated by varying the free parameters, one after one, viz. hydrogen density, underlying luminosity, effective blackbody temperature and abundances of only those elements which showed observed lines. The abundances of other elements, which do not show any emission line, were fixed at solar values. Since, novae ejecta are not homogenous in density, we assume that the ejecta is composed of at least two different density regions – one for the higher density to fit the lower ionization lines and the other for the lower density to fit the higher ionization lines. To reduce the number of free parameters in the final model, each component is subjected to the same parameters except the hydrogen densities at the inner radius and the covering factors assuming that the sum of the two covering factors be less than or equal to 1. Thus, the overall number of free parameters increases by 2 due to the second component's initial density and covering factor. The final model line ratios were