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A NEW METHOD OF DETERMINING THE EJECTED MASS OF NOVAE

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Abstract.

A new method of determining the ejected mass of novae based on simple, reasonable assumptions is presented. This method assumes that the remnant mass on the white dwarf is the same as that from the previous nova outburst. The hydrogen, helium, and metal abundances of the accreted material from the secondary must also be known or assumed. The white dwarf's mass has a small effect because the amount of hydrogen consumed during the thermonuclear runaway only depends weakly upon this mass. If the composition of the ejecta and the time of the remnant shell burnout are determined from observations, then the ejected and remnant masses can be deduced. At present only a sharp decrease in the X-rays observed by ROSAT has been attributed to this remnant burnout and only for two novae: GQ Mus and V1974 Cyg. The ejected and remnant masses for these two novae are calculated. If other indicators of nova remnant burnout, such as a rapid decrease in high-ionization lines, can be identified, then this method could be applied to additional novae.

1. Introduction

The ejected mass is one of the most basic quantities in nova studies, but it has been very difficult to determine observationally. Most ejected mass determinations involve relating an electron temperature from the ratio of a forbidden line pair, the emission measurement from the flux of a hydrogen

line, and an estimate of the ejecta's volume. The nonuniformity of the ejecta causes a large uncertainty in these mass determinations.

Nova ejecta consists of material from three sources: accreted material from the secondary, remnant material from the previous outburst, and dredged-up white dwarf material. These three sources are shown schematically as layers on the white dwarf in the first panel of the drawing in Figure 1. The next panels picture the mixing due to the thermonuclear runaway (TNR), the ejection and remnant hydrogen shell burning, and finally, the burned-out remnant left on the white dwarf. When more material is accreted from the secondary, the cycle starts over again. This simple drawing illustrates two of the assumptions used. First, materials from the three sources are thoroughly mixed by the TNR, and the mass of the remnant is the same as that from the previous outburst. These assumptions are supported by numerical simulations. Starrfield et al. (1972) found that the entire envelope above the TNR region is strongly convective and Shara, Prialnik, and Kovetz (1993) have shown that the remnant masses are very similar after the first few outbursts.

Figure 1. The nova cycle showing (a) the accretion of material onto the white dwarf, (b) the mixing due to the TNR, (c) the ejection and remnant burning, and (d) the burned-out remnant.

2. Formulation of the Problem

With the above assumptions, equating the mass abundances of hydrogen, helium, and the metals before and after the TNR produces the following equations:

$$M_{acc}X_0 = M_{tot}(X + \Delta X_{run}) \quad (1)$$

$$M_{acc}Y_0 + M_{rem}(X + Y) = M_{tot}(Y - \Delta Y_{run}) \quad (2)$$

$$M_{dg} + M_{rem}Z + M_{acc}Z_0 = M_{tot}(Z - \Delta Z_{run}) \quad (3)$$

$$M_{tot} = M_{acc} + M_{rem} + M_{dg}, \quad (4)$$

where the abundances with a zero subscript and no subscript are for the secondary, and the mixed materials, respectively; M_{acc} , M_{rem} , and M_{dg} are the accreted, remnant, and dredged-up white dwarf masses; and ΔX_{run} , ΔY_{run} , and ΔZ_{run} are the changes in the composition due to the TNR. The composition of the white dwarf is assumed to be all metals. This formulation is not new; variations of these equations have been described by Sparks et al. (1988), Prialnik (1990), and Fujimoto and Iben (1992). Note that any mixing mechanism before the TNR does not affect to this formulation.

Solving the above equations gives only a ratio of the individual mass components to the total mass. Another condition for one of these masses must be known in order to determine the individual mass components. The time for hydrogen burnout of the remnant mass provides such a condition. Equating the energy radiated from the remnant to the nuclear energy available from hydrogen burning gives

$$\int L dt = E_H X M_{rem}, \quad (5)$$

where L is the luminosity and E_H is the nuclear energy available from burning hydrogen to helium. We will assume that the luminosity is constant in time and equal to the equilibrium hydrogen shell burning plateau luminosity. Therefore,

$$L_{eq} \Delta t = E_H X M_{rem}. \quad (6)$$

3. Results

Let us now consider GQ Mus, a nova that erupted in 1983. Hassall et al. (1990) derived abundances of $X = 0.27$, $Y = 0.32$, and $Z = 0.41$ for its ejecta. It is assumed that the secondary has solar abundances ($X_0 = 0.71$,

$Y_0 = 0.27$, and $Z_0 = 0.02$). We will further assume that the primary is a $1.0 M_\odot$ CO white dwarf. The heavy element composition of the ejecta (Hassall et al., 1990) strongly suggests that the TNR occurred on a CO white dwarf, and $1.0 M_\odot$ is a reasonable mass for such a white dwarf. Fortunately, the results depend only weakly on this chosen mass. For a $1.0 M_\odot$ white dwarf, the amount of hydrogen burned during the TNR to produce enough energy to lift material to the white dwarf's Roche lobe radius (which for most nova binary systems is $\sim 1.0 R_\odot$) is 0.04 (see Fujimoto and Iben, 1992 for a more detailed discussion). For a TNR on a CO white dwarf, hydrogen is combined with C^{12} to produce mostly C^{13} and N^{14} (Starrfield, Truran, and Sparks, 1975). Thus, we will use $\Delta X_{run} = \Delta Z_{run} = 0.04$ and $\Delta Y_{run} = 0.0$.

Substituting these values into eqs.(1-4) gives $M_{rem}/M_{tot} = 0.34$, $M_{acc}/M_{tot} = 0.44$, and $M_{dg}/M_{tot} = 0.22$. Since ΔX_{run} and ΔZ_{run} are small compared to the observed $X(= 0.27)$ and $Z(= 0.41)$ values, the assumed value of the white dwarf's mass has only a small effect on the final results. Recently, the X-rays from GQ Mus observed by ROSAT (Shanley et al., 1995) have shown a sharp decrease 11 years after outburst. They interpreted this decrease as the turn off of the remnant hydrogen shell source. Using the plateau luminosity of the appropriate hydrogen shell burning model of Fujimoto and Iben (1992) in eq.(6), we calculate a remnant mass of $1.7 \times 10^{-5} M_\odot$ for GQ Mus. This mass combined with the previous results yields an ejected mass of $3.3 \times 10^{-5} M_\odot$ for GQ Mus.

One caveat to this simplified picture is that, according to Fujimoto and Iben (1992), the radius of this $1.7 \times 10^{-5} M_\odot$ remnant will be much larger than any reasonable Roche lobe. In other words, there will be a common envelope around the binary, and the composition of the remnant may be a mixture from the ejecta and the secondary. As an extreme case, we can assume that the remnant material comes entirely from the secondary. Thus, the X in eq.(6) and the X , Y , and Z on the left hand side of eqs.(2) and (3) will have a zero subscript signifying material from the secondary. Under these conditions the remnant mass is $5.0 \times 10^{-6} M_\odot$, and the ejected mass is $2.0 \times 10^{-5} M_\odot$. A white dwarf remnant formed from a common envelope will lie somewhere between these two extreme cases, and thus the ejected mass lies between 2.0 and $3.3 \times 10^{-5} M_\odot$.

V1974 Cyg is the only other nova observed by ROSAT to have a sharp decrease in X-rays. Its X-ray flux turned off 18 months after outburst (Krautter et al., 1995). Recent photoionization models of the emission lines by Austin et al. (1995) constrained the helium abundance from 0.22 to 0.46 and the metals from 0.36 to 0.44. Since the emission lines indicate a large abundance of O, Ne, and Mg, we will assume that the TNR occurred on a $1.25 M_\odot$ ONeMg white dwarf. The amount of nuclear burning required to lift material off of a $1.25 M_\odot$ white dwarf indicates that $\Delta X_{run} = \Delta Y_{run}$

$= 0.08$ and $\Delta Z_{\text{run}} = 0.0$ (see Fujimoto and Iben, 1992 and Politano et al., 1995). Here the assumed white dwarf's mass is more critical to the final results than in the case for GQ Mus. Using the largest values for both helium and the metals, we calculate a remnant mass of 8.7×10^{-6} and $8.7 \times 10^{-7} M_{\odot}$ and an ejected mass of 7.1×10^{-6} and $1.8 \times 10^{-6} M_{\odot}$ when the composition of the remnant mass is like that of the ejected mass and the secondary, respectively. For the smallest deduced values of helium and metal abundances, the remnant mass is 2.1×10^{-6} to $8.7 \times 10^{-7} M_{\odot}$ for the same two sources of the remnant mass composition. However, since the lowest limit of the helium abundance can be produced during the TNR, no upper limit constraints can be placed on the ejected mass. Thus, we have found only a lower limit of $1.8 \times 10^{-6} M_{\odot}$ for the ejected mass of V1974 Cyg.

4. Conclusions

This method uses the observed abundances from the ejecta and the turn-off time of the remnant burning to determine the ejected and remnant masses of a nova. At present only the rapid decrease in X-rays observed by ROSAT has been attributed to the remnant burnout and only for two novae: GQ Mus and V1974 Cyg. For GQ Mus, we find an ejected mass between 2.0 and $3.3 \times 10^{-5} M_{\odot}$, whereas Hassall et al. (1990) estimated it to be $8.4 \times 10^{-5} M_{\odot}$. Stringfellow and Bowyer (1994) detected V1974 Cyg with the Extreme Ultraviolet Explorer ~ 285 days after its outburst. They fit their data best with a hot white dwarf atmosphere of $4.0 \pm 0.5 \times 10^5$ K and a column hydrogen density near $3 \times 10^{21} \text{ cm}^{-2}$. These high temperatures require that the radius of the remnant on the white dwarf be small. For our assumed white dwarf mass of $1.25 M_{\odot}$ and their temperatures, the unburnt remnant mass is estimated to be from 5.0 to $5.6 \times 10^{-7} M_{\odot}$, using Fujimoto and Iben's (1992) graphs of equilibrium models. Since at the time of their observation, approximately one half of the remnant mass has burned out, this range of remnant masses is entirely consistent with our calculated range of 8.7×10^{-7} to $2.1 \times 10^{-6} M_{\odot}$. Krautter et al. (1995) calculated an upper limit of $2 \times 10^{-5} M_{\odot}$ for the remnant mass of V1974 Cyg by equating its potential energy to the emitted energy from the latter part of the X-ray light curve. Although these various deduced masses for the remnant of V1974 Cyg are consistent, there is a large discrepancy in estimations of its ejected mass. We derive a lower limit of $1.8 \times 10^{-6} M_{\odot}$ for the ejected mass in V1974 Cyg, whereas Shore et al. (1993) find a lower limit of $10^{-4} M_{\odot}$. Future abundance or white dwarf mass determinations of V1974 Cyg can provide upper limits on its ejected mass with this new method. However, it is unlikely that the calculated ejected mass will be as

large as $10^{-4} M_{\odot}$. These ejected mass discrepancies must be resolved. If other criteria for the burnout of the remnant shell, for example, a rapid decrease of a high-ionization line, could be established, then this method could be applied to other novae.

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