Physical Properties and Abundances of Novae in the Nebular Phase.

M.A.J. Snijders

Astronomisches Institut Tübingen

Abstract

We discuss the derivation and behaviour of temperatures and densities of nova ejecta during the nebular stage. A systematic comparison is made between fairly complete sets of abundances for 3 C/O and 2 Neon novae. The abundances in the ejecta might influence the formation and composition of circumstellar dust in novae.

1. Introduction

During the nebular stage of the nova outburst we study a teneous, optically thin gas with a low filling factor and initially, a rapidly increasing degree of ionisation. In this review I will make use of recent reviews of the nova outbursts [1, 2, 3] and concentrate on just two points: temperatures and densities during the early nebular stage and the abundances in the ejecta. Here early nebular stage means the period following the outburst where high quality nebular spectra can be easily obtained with the IUE satellite [4]. Abundances are of special interest because recent results make it for the first time possible to compare a large set of abundances for 6 recent novae and make a systematic comparison between C/O and Neon novae.

2. Physical conditions in the ejecta.

Pictures of the ejecta [5, 6, 7] at the nebular stage of the outburst show an inhomogeneous shell around the central object with many density enhancements. Which such a structure the, often very low, filling factors of the ejecta [eg 8, 9] are not surprising. As the emissivity of the gas goes as the square of the density most of the detected emission lines will come from the densest knots, as long as the temperature and degree of ionization do not vary too much over the shell and the density is less then the critical density for the emission line(s) studied.

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For a physical study of the ejecta information on the gas temperature and density are of prime importance. Following the launch of the IUE satellite [4] a simple method was develloped to derive the gas temperature from diagnostic line ratios involving collisionally excited and dielectronic recombination lines, which depend essentially only on the temperature [10, 11]. This method was first develloped for the study of V1668 Cygni [10] and greatly facillitates the analysis of gas in the nebular stage. The earlier methods depend on varies diagnostic line ratios of collisionally excited forbidden and/or intercombination lines and have the disadvantage that the results are simultaneously sensitive to both temperature and density. The result of these developments is a "standard" approach for deriving the temperatures and densities of the gas: measure emission line fluxes, apply a reddening correction, derive temperatures from the dielectronic recombination line ratios and finally using the now known temperatures derive the density from line ratios involving forbidden and intercombination lines. Various forms of this approach have been used for the study of V1668 Cyg [10], V693 CrA [12], V1370 Aql 82 [9, 13], GQ Mus [8, 14, 15] and PW Vulp [16]. As the stronger dielectronic lines [17] and the intercombination lines are all in the ultraviolet and the important forbidden lines are in the optical and infrared parts of the spectra [e.g. 18] simultaneous observations with reliable absolute calibrations in the optical and ultraviolet regions are essential.

The results show that a wide range of temperatures is present in the ejected material in the early nebular stage with increasing ionization and increasing electron temperatures being closely associated. Typical temperatures for the material emitting C^{++} lines are 9000K - 11000K, for C^{+++} emitting gas temperatures of 10000K - 13000K are found and the gas emitting N^{4+} emission lines has temperatures in the 13000K to 18000K range [8, 10, 12, 14, 15, 16]. These temperature ranges overlap but in any individual set of data the gas which emits C^{++} lines is never hotter and nearly allways clearly cooler then the gas which emits C^{+++} lines and gas which emits N^{4+} lines is allways the hottest material observed.

The densities in the early nebular stages are usually derived from line ratios involving OIII] and [OIII] and/or NII] and [NII] lines [e.g. 8, 9, 15] and typical densities are in the range log(Ne) is 6.5 to 8.5 [8, 9, 10, 13, 14, 15, 16]. In practice these numbers should be treated with caution as their interpretation can be drastically modified by the peculiarities of atomic physics and the oxygen overabundances of nova ejecta. The [OIII] 5007A line has a critical density of log(Ne) = 5.8, or as the observed densities are well above this critical density, collisional deexcitation will be of major importance. Collisional deexcitation is proportional to the density and at high densities the [OIII] 5007 line will become undetectable with respect to nearby lines not sensitive to collisional deexcitation. As oxygen is overabundant in nova ejecta by 1 to 2 orders of magnitude (section 3) the [OIII] 5007 line should become undetectable at densities somewhat higher then 6.8 to 7.8. In fact the maximum densities derived in the early nebular stage from [OIII] lines vary from 7.1 to 8.4 [13, 16].

For GQ Musca densities were derived at the start of the nebular phase from the ultraviolet NIII] quintet line ratios, which depend only on the density, and the optical [OIII] lines. The [OIII] lines lead to a constant density of log(Ne) = 7.6 but the NIII] line ratios lead to densities of 8.7 to 8.3 roughly decreasing as the square of the time since the outburst. The bulk of the gas in this case is at the higher densities and the

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less dense, outer edges of the high density clouds presumably emit the [OIII] 5007 lines [8,14].

The simple argument that when we can see strong [OIII] 5007 lines the density should be less then their critical density [19, 20] can lead to very large underestimates of the actual density. This is well documented for the case of GQ Musca where people from the same group first used the critical density argument [19] and later correct nebular physics [15] and the differences in their results are clear testimony to both the size of the possible errors and the rapid increase in our understanding of the nebular ejecta.

Available evidence [8, 14, 21] suggests that the density decreases slightly faster then the square of the time since the outburst. For the rapidly expanding nova shells where the expansion velocity of the shell is much larger then the sound velocity of the gas this result is not surprising.

As a consequence of this rapid decrease in density the surface brightness of old nova shells decreases very rapidly as well, which makes observations difficult. Recently spectroscopy of old nebular ejecta has become available which shows some remarkable spectra. Due to the large overabundances of heavy elements (section 3) cooling of the ejecta by emission lines is extremely efficient. In many old novae a central ionizing source is no longer available and the gas cools then rapidly. Gas temperatures of only 500K for DQ Her 1934 [6] and 800K for CP Pup 1942 [7] were derived.

While most of the nebular emission is undoubtedly powered by radiation [eg 15] shock heated coronal gas is also present in some objects. Good examples are V1500 Cyg [22] and the recurrent nova RS Oph [23].

3. Abundances

Extensive observational and theoretical studies of the abundances in nova ejecta have recently resulted in the recognition of the existence of at least 2 different groups of classical novae [eg 1, 2, 3]. Besides classical novae which have large CNO overabundances the new class has large overabundances of neon and heavier elements as well [12, 13]. From a recent review [3] of nova abundances it is clear that large overabundances of heavy elements do occur in all objects so far studied. In table 1 we collect abundances for recent novae for which, with exception of V1500 Cyg, the ultraviolet spectrum was included in the analysis. The fundamental advantage of the ultraviolet region of the spectrum is that some elements (Mg, Al and Si) and many stages of ionization (eg O^{+++}, N^{+++} and N^{4+}) do not have lines at present suitable for abundance studies in the optical part of the spectrum. It is however not possible, as yet, to derive sulpher or iron abundances from the ultraviolet nebular spectra of novae. Further advantages of concentrating on recent novae include the facts that it is much easier to check on modification of the abundances in the ejecta through dust formation [9], possible contamination of the ejecta by swept up interstellar material can be ignored, the possibility to construct a fairly complete set of abundances and finally all the recent novae were

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studied while the typical gas temperature was still around 10000K to 15000K. For this latter region reasonably well known atomic parameters are available [24] while for the low temperature gas present in some of the older novae rather uncertain recombination coefficients have to be used [eg 7].

The abundances in Table 1 were compiled from the literature with one exception: for V1668 Cyg the Mg, Al and Si abundances were derived for this paper using the IUE ULDA data base [25] to obtain abundances averaged over 3 early nebular epochs using the methods from reference [10].

For V1370 Aql the abundances are given twice: first the observed gas phase abundances after dust formation and then for the depleted elements the estimated original abundances [9]. V1370 Aql formed both amorphous carbon smoke and silicates [9] and it was realised almost immediately that the observed gas phase abundances could not be understood from standard nuclear processes [13]. It was subsequently shown that the gas phase silicon abundance was drastically diminished during the dust formation and that at the end of the dust formation stage the total mass of the dust was comparable to the total mass in the gas [9]. Normal nuclear burning was assumed in estimating the corrections, this can be only a first order approximation for the explosive nuclear burning in a nova, but it gives an idea of the size of the effects we can expect.

The abundances in table 1 are subject to the usual random and systematic errors and are probably good to a factor 2 or 3 with respect to hydrogen. However the abundances of H and He with respect to each other and of C, N, O and Ne again with respect to each other are much better determined as the systematic errors tend to be the same. Major sources of systematic errors are the temperatures in the ejecta: H and He abundances do not depend on these but nearly all heavy element abundances depend on $e^{-}(h\nu/kT)$ and any error in the temperature will systematically change all abundances with respect to H and He [10]. Similar as C, N, O, Mg, Al and Si abundances are derived from UV lines and the hydrogen abundance from optical lines errors in the reddening corrections will cause systematic errors in abundances. The different abundances obtained for GQ Musca [14, 15] are largely due to a different reddening correction. Finally Mg, Al, Si and S have much larger ionization corrections then C, N, O and Ne, when both IUE and optical spectra are used for the analysis, and this can cause systematic errors of the heavy elements with respect to each other.

Table 1. Abundances for recent novae.

	Solar System	V1500 Cyg 1975	V1668 Cyg 1978	V693 CrA 1981	V1370 Aql 1982		GQ Mus 1983	PW Vulp 1984
ref	[26]	[21,27]	[10,28]	[12,29]	[9]	[9]	[8,14]	[16]
H	1.0	1.0	1.0	1.0	1.0		1.0	1.0
He	6.8E-2	1.5E-1	1.2E-1	2.8E-1	4.5E-1		2.9E-1	1.2E-1
C	4.2E-4	8.5E-3	8.0E-3	1.5E-3	5.9E-2	1.0	4.9E-3	1.1E-2
N	8.7E-5	5.1E-3	2.1E-2	2.1E-2	2.1E-1		5.1E-2	1.7E-2
O	6.9E-4	5.5E-3	1.7E-2	2.7E-2	6.5E-2	1.7	4.3E-2	1.2E-2
Ne	9.8E-5	8.7E-4	<7.5E-4	3.0E-2	5.3E-1		6.3E-4	2.0E-4
Na	2.3E-6	–	–	2.5E-4	–		–	–
Mg	4.0E-5	–	1.2E-4	1.1E-3	5.7E-3	1.5E-1	2.2E-4	2.3E-5
Al	3.2E-6	–	≤6.7E-5	4.4E-4	–		<7.6E-5	–
Si	3.8E-5	–	2.8E-4	3.2E-4	1.3E-3	1.6E-1	3.6E-4	4.3E-4
S	1.9E-5	<6.E-5	–	–	6.4E-2		1.8E-4	–
Fe	3.4E-5	1.4E-5	–	–	1.7E-3	1.6E-2	3.1E-5	3.4E-5

Remarks to table 1: abundances by number with respect to Hydrogen.

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All nova in table 1 have small but highly significant Helium overabundances [see also 3], overabundances of carbon and oxygen by 1 to 2 orders of magnitude and nitrogen is typically overabundant by 2 to 3 orders of magnitude. Overabundances of heavier elements vary widely. From a review of work on older novae [3] it is clear that the ejecta of T Aur, HR Del, DQ Her and RR Pic show the same pattern of overabundances for H, He, C, N and O.

V1668 Cyg, GQ Mus and PW Vulp are C/O novae and their abundances of Ne, Mg, Al, Si and S are typically solar to 10 times solar while the Iron abundance is solar. V693 CrA and V1370 Aql are Neon novae and there are problems with the data for both of these objects. For V1370 Aql the accuracy of the dust depletion corrections is uncertain in particular for iron [9] and as no Na or Al lines were observed at the epoch the abundances were determined no abundances for these elements were derived. In view of the strength of AlIII and NaI absorption lines and AlII] and AlIII emission lines during the early stages of the outburst [9] it seems probable that both elements were substantially overabundant just as in V693 CrA. Using simple scaling relations like those used for the study of V693 CrA [12] it is straitforward to show that aluminium was probably at least 2 orders of magnitude overabundant in V1370 Aql before depletion became important. Of the three recent Neon novae, Nova Vulp 1984 no 2 is the third neon nova, 2 formed extensive silicate dust [9, 32, 33] and if the large overabundances of the heavier elements in Neon novae favor the formation of Silicon based dust V693 CrA could have formed dust too. In fact this is indeed the case [32,33], and it is possible that the abundances of V693 CrA listed in Table 1, in particular Silicon, are affected by dust depletion as well.

From the small sample discussed here it appears that the formation of silicon based dust is rather easy for Neon novae. There might also be a connection between the detection of amorphous carbon dust in the ultraviolet spectra of V1370 Aql and the fact that it has by far the highest carbon abundance of all objects in Table 1.

The nature of V1500 Cyg, which was originally classified as the first Neon nova [21], is not clear. Compared to the two true Neon novae the Neon overabundance is small but it is slightly larger then the Neon abundances for the three C/O novae. Unfortunately the Mg, Al and Si abundances, which are enhanced too in true Neon novae, are not known. The sulpher and iron abundances resemble those of C/O novae but the only Neon nova we can compare with is V1370 Aql which is such a peculiar object [13 ,34] that it might not be a good representative of the class.

It is now generally accepted that the most reasonable way to generate the large overabundances observed in classical novae is if material from the underlying white dwarf is mixed into the newly accreted shell [eg 1, 34]. The C/O novae then occur on a white dwarf with surface layers enriched in carbon and/or oxygen and the Neon novae occur on white dwarfs where the surface layers are heavily enriched in oxygen, neon and magnesium [eg 1, 35]. The consistenly high nitrogen abundances are a result of the explosive nuclear burning which converts carbon and/or oxygen preferentially to nitrogen.

This is the first time that a systematic comparison of a fairly complete sample of abundances of light elements in nova ejecta has been possible and systematic patterns in the abundance peculiarities are becoming clearer. The near solar abundances of all

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elements heavier then Oxygen for the C/O novae is in the present sample for the first time obvious. For the Neon novae the, often large, overabundances of all elements from Nitrogen to Silicon seems clear for both V693 CrA and V1370 Aql but ultraviolet observations with ST of V1500 Cyg are urgently required to clarify its nature. The nuclear burning networks in models for the nova outburst itself tend to be fairly small and calculations where the structure of the burning shell is taken from detailed outburst models but where a more complete nuclear reaction network is used to estimate the abundances in the ejecta are therefore helpfull [34]. From these it appears possible to have C/O novae with small neon overabundances, a factor 30 in the most extreme case [34], and the sulpher overabundance in V1370 Aql can be explained too. Note however that this again raises questions about the nature of V1500 Cyg where neon is only 9 times [27], or perhaps 24 times [21], overabundant. V1370 Aql is indeed a most peculiar object [9]: the carbon overabundance is difficult to generate in current models of Neon novae [eg 34], and it is extremely difficult to generate the observed iron overabundance [eg 36]. V693 CrA has the lowest carbon abundance of all the novae in table 1 in agreement with current models for Neon novae but if V1500 Cyg is indeed a Neon nova too carbon overabundances in Neon novae could actually be quite normal.

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