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ON THE ORIGIN OF THE OBSERVED KNOTS IN NOVAE

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ABSTRACT

Recent observations with the Goddard High Resolution Spectrometer have established the existence of fragmented matter in Nova Cygni 1992. We discuss this phenomenon and show that it might result from a thermal convective/absolute instability.

Subject headings: hydrodynamics — instabilities — novae, cataclysmic variables

1. INTRODUCTION

A recent observation performed with the Goddard High Resolution Spectrometer (GHRS) by Shore et al. (1993) established the presence of knots in Nova Cygni 1992. The existence of knots was conjectured in the past as an essential ingredient in interpreting observations of novae (Krautter et al. 1984; Williams et al. 1991; Saizar & Ferland 1994). However, the conjecture never received a direct and solid confirmation such as the new observation by Shore et al. (1993) provides. It is the excellent spectral resolution of the GHRS which allowed the tight confirmation of the appearance of knots. Shore et al. (1993) report the detection of the knots (see § 3.4 of that work) as soon as the nova went into the nebular phase and the lines became optically thin.

In particular we note that Shore et al. (1993) point out the large differences between the shapes of line profiles of novae. It is on the background of this large variety in shapes that they find some novae which have a very close resemblance to Nova Cygni 1992 (HR Delphini 1977 and V1500 Cygni 1975). However, Shore et al. (1993) state that this particular resemblance among the above three novae may be a consequence of the fact that Nova Cygni 1992 is the best observed nova of the three. Specifically, an observation of the older novae with the same resolution as used in the observation of the more recent one might have detected differences in line profiles. We further note that in the interpretation of the early nebular spectrum of Nova Vulpeculae 1984, Saizar et al. (1992) claim that the nova shows a uniform spherical shell at this phase. However, Saizar & Ferland (1994) resort to a "two-phase" model to explain the line structure at later stages. Shore et al. (1993) also established that the knots appear close to, or at, the lower boundary of the expanding shell, where lower is close to the white dwarf (WD) and upper is far away from it.

The above facts led Shore et al. (1993) to conclude that the knots were present from the early stage of the explosion and appeared only when the ejecta became optically thin in lines. They support their claim by noting the structure in C III lines. This line structure is present in *IUE* low-resolution spectra since day 130. Hence, Shore et al. (1993) conjecture that the source of the knots is Rayleigh-Taylor instability (RTI) excited in the first few seconds of the explosion. This is a reasonable interpretation in view of the fact that it is now well established that many explosive processes are RT unstable. Furthermore, most shocks that propagate into stratified media are found to be RT unstable (Chevalier, Blondin, & Emmering 1992).

RTI leads to a "finger"-like structure. The fingers subsequently undergo a Kelvin-Helmholtz instability (KHI), and a mushroom-like structure is formed at their tips (Chevalier et al. 1992). In light of the universality of the RTI in shock structure, it is difficult to understand the variety in line shapes observed in novae during the nebular phase. In making this statement, we assume à la Shore et al. (1993) that this richness in the appearance of nova lines at the nebular phase does not result from the quality of the instrumentation used in the past. Thus, we assume that some nova ejecta contained knots in large observable amounts, while others had a vanishingly small amount of knots. We interpret this scatter in the observational features as indicating that the instability occurs on different length scales. On the other hand, the universality of RTI is a result of the lack of such a scale (in the local case). Thus, the hypothesis that the RTI is the one that leads to the formation of the knots is not compatible with the inferred inherent variety of nova observations. Moreover, the RTI is excited in the early expansion. At this stage the ejecta is opaque to radiation. Energy transport effects are expected to homogenize the structure eventually. Numerical simulations that evolve the flow long enough after the excitation of the RTI show that eventually it leads to a formation of a completely mixed zone with vanishing density fluctuations and a turbulent velocity field (Fryxell 1994). The final state resembles that of an incompressible turbulent fluid.

The restoration of the stratified structure of the ejecta (vanishing density and temperature fluctuations) is expected to occur on very short timescales. Chevalier et al. (1992) provide a semiempirical formula for the width of the mixing zone as a function of time and acceleration. This formula allows one to establish that all the ejecta will be mixed once a spherical shock has propagated through the ejecta.

All suggested explosion mechanisms for novae (global thermonuclear runaways [GTNRs] or local thermonuclear runaways [LTNRs]) lead to an RTI in a short period (Shankar, Arnett, & Fryxell 1992; Shankar & Arnett 1994; Godon & Shaviv 1995). Hence, *theoretical expectations are that the RTI will make all novae look alike during the photospheric phase and even later*. In fact, nova spectra look very much alike during the photospheric phase (Saizar et al. 1992; Hauschildt et al. 1994). In summary, since the RTI leads to a uniform shell, another instability is required to explain the appearance of knots and the variety in nova appearances.

An instability that possesses a length scale that strongly depends on the features of a given nova (the WD remnant, chemical composition, and the ejected mass) is the thermal instability. The relevant scale of the thermal instability is the Field length scale (Field 1965). This instability is expected to occur as soon as the ejecta becomes optically thin, namely, at the right time for the appearance of the knots observed by Shore et al. (1993).

The analysis of Field (1965) was carried out for a uniform medium at rest. The element of motion in novae and the stratification complicate the situation mathematically. Balbus (1986) and Balbus & Soker (1989, hereafter BS) developed a very convenient mathematical tool for studying development of thermal instabilities in a moving medium. They implemented their result to the stability of stellar winds.

BS find that there is no pronounced instability in supersonic flow. However, the formation of knots with 100% density contrast relative to the diffuse medium is a possibility. Note that the density contrast reported by Shore et al. (1993) is less than 10%.

The aim of this Letter is to provide theoretical evidence that the observed knots might result from a thermal instability of the ejecta as it becomes optically thin. This does not imply that the RTI is not present. As a matter of a fact, the RTI most probably exists but cannot reconcile the large variety in the observations of novae. Therefore, we study below the condition for the formation of a thermal instability in the ejecta from novae. The structure of this Letter is as follows: in § 2, we study the typical scale for a thermal instability to develop as the nova goes into the nebular phase. In § 3, we provide a brief outline of the BS formalism and results and discuss the applicability to novae. Section 4 is a summary.

2. TYPICAL SCALES

A lower limit on the critical scale for the onset of a thermal instability is the Field (1965) wavelength. This scale is given by

$$\lambda_{\rm F} = \sqrt{\frac{\kappa_{\rm SH} T}{n_e^2 \Lambda(T)}} = \begin{cases} 9.8 \times 10^8 \left(\dfrac{n_e}{10^6\ {\rm cm}^{-3}}\right)^{-1} \left(\dfrac{\ln \Lambda_c}{25}\right)^{-1/2} \left(\dfrac{T}{10^4\ {\rm K}}\right)^{1.25-60Z} {\rm cm}, & T > 10^4\ {\rm K}, \\ 8.5 \times 10^{10} \left(\dfrac{n_e}{10^6\ {\rm cm}^{-3}}\right)^{-1} \left(\dfrac{\ln \Lambda_c}{25}\right)^{-1/2} \left(\dfrac{T}{10^4\ {\rm K}}\right) {\rm cm}, & T < 10^4\ {\rm K}, \end{cases} \tag{1}$$

where $\lambda_{\rm F}$ is the Field wavelength, $\kappa_{\rm SH}$ is the Spitzer-Härm conductivity, T is the gas temperature, $\Lambda(T)$ is the cooling function, n_e is the electron number density, Λ_c is the Coulomb logarithm, and Z is the heavy element mass fraction. The cooling function dependence on Z was taken from Theis, Burkert, & Hensler (1992). From equation (1) we see that the Field wavelength is much shorter than the width of the spherical shell forming the ejecta after about a year of expansion when $\Delta R \sim 10^{15}$ cm. Thus, knots of a size much smaller than the size of the ejecta can form. However, in the case of a shell that is illuminated from below by a star, the heating cannot be ignored. The heating by the underlying WD makes the scale of the instability depend on the evolution of the WD remnant. Furthermore, the expanding shell has a differential velocity law. It has been established by BS that the critical wavelength in such cases depends on the rate of the differential velocity law as well.

An important question for instability in a dynamic medium is the rise time of the instability. A lower limit on this timescale is provided by the isobaric cooling time which in the present case is given by

$$\tau_{\rm cool} = \begin{cases} 5.5 \times 10^{-4} \left(\dfrac{n_e}{10^6\ {\rm cm}^{-3}}\right)^{-1} \left(\dfrac{T}{10^4\ {\rm K}}\right)^{1-120Z} {\rm yr}, & T > 10^4\ {\rm K}, \\ 4.3 \left(\dfrac{n_e}{10^6\ {\rm cm}^{-3}}\right)^{-1} \left(\dfrac{T}{10^4\ {\rm K}}\right)^{1/2} {\rm yr}, & T < 10^4\ {\rm K}, \end{cases} \tag{2}$$

where $\tau_{\rm cool}$ is the isobaric cooling time. It is clearly seen that once the ejecta becomes optically thin in the lines, the instability develops almost instantaneously. In practice, the cutoff introduced in the cooling function at 10^4 K is artificial and represents a very steep rise in the cooling function at this temperature. The rise time of the instability is also expected to be determined by the details of the heating function that in turn depend on the ionization state of the nebula, the chemical composition, and the evolution of the WD remnant. Thus, the thermal instability can create the observed knots in the ejecta.

3. ANALYSIS

In order to assess the applicability of the BS formalism and results to the nova case, we outline briefly the physical assumptions underling their derivation. The unperturbed solution is homogeneous, spherically symmetric, and in thermal equilibrium. The solution is assumed to satisfy the following equations:

$$\frac{d \ln \rho}{dt} + \nabla \quad {\bf v} = 0, \tag{3}$$

$$\frac{d{\bf v}}{dt} + \frac{1}{\rho} \nabla P + \nabla \Phi = 0, \tag{4}$$

$$\frac{3}{2}P\frac{d\ln(P\rho^{-5/3})}{dt} + \rho\mathscr{L}(\rho, P) - \nabla \quad (\boldsymbol{\kappa}_{\rm SH}\nabla T) = 0, \tag{5}$$

where ρ is the gas density, $\boldsymbol{v}$ is the gas velocity, Φ is the gravitational potential, P is the gas pressure, and $\rho\mathscr{L}(\rho, P)$ is the net heating cooling function. This set of equations is supplemented by an ideal gas equation of state.

An attempt to solve the Eulerian perturbation equations including all modes is mathematically cumbersome and makes the physical analysis difficult. BS note that the incompressive modes are the unstable (condensing) modes. Thus, the analysis is performed under the assumption that the energetics of the perturbation is not affected by the acoustic or compressive modes. Therefore, in the perturbed energy equation (and *only* in the energy equation) one may set $\delta P = 0$ (the Boussinesq approximation). The analysis of BS was carried out only in the equatorial plane, and hence it is a two-dimensional perturbation.

A major physical advantage results from the fact that the evolution of the perturbation is studied in a comoving frame. A simple model to understand the physical setup is the following one. Imagine an observer comoving with the flow and with a coordinate r'. The flow experiences a Eulerian perturbation at r when the observer coordinates satisfy $r = r'$. The question is whether or not the comoving observer will see the perturbation grow.

BS provide a solution for the perturbation equations for a supersonic steady state flow which is allowed to cool. Momentum balance was not considered in light of the fact that the flow was assumed to be highly supersonic. We summarize that all the prerequisites for the BS analysis are satisfied in the nova's expanding envelope. BS find in their idealized cases a moderate rise. We note that the observations require only a moderate rise. Indeed, BS find that in their case $\delta\rho/\rho < 100\%$, while Shore et al. (1993) observe $\delta\rho/\rho \approx 10\%$.

4. SUMMARY

We conclude that the presence of knots in the ejecta of novae does not constrain or affect in any way the GTNR or LTNR theories. The appearance of the knots is an intriguing astronomical question, although the observed effect in most novae is rather mild. We presented a case in which knot formation in nova ejecta occurs as novae go into the nebular phase. The knots in this case are a natural result of a mild thermal instability; by mild we mean that the density contrast is relatively small. Our motivation for presenting the thermal instability is the fact that the phenomenon is observed in some novae.

We further strengthen this assumption by the fact that some novae show the knots at different stages of the nebular phase of the expansion (Nova QU Vulpeculae 1984). The value of $\delta\rho/\rho$ is mild in both cases and is in good agreement with the analysis of BS. If the diversity in the observations with regard to the presence of knots is not an instrumental effect, it points against the possibility that the knots are a result of an RTI, which will tend to have a more universal nature. Furthermore, if the knots were present earlier in the expansion, they should have been observed in P Cygni–shaped line profiles when the photosphere retreats in the ejecta. The fact that the knots are not observed in the P Cygni–shaped lines might result from the low spectral resolution of *IUE*. High resolution of P Cygni line profiles in novae is required to solve this problem.

It seems that in the case of Nova Cygni 1992 and Nova QU Vulpeculae 1984 the separating line between the uniform region and the region containing the knots is creeping into the ejecta from below at the nebular phase. This is slowly dissolving the ejecta from the side of the WD outward. Note that Shore et al. (1993) suggest that the knots are not comoving with the diffuse matter. In such a case it is expected that the knots will be destroyed on a dynamic timescale by a KH instability on a dynamic timescale (of the knot's motion relative to the diffuse matter).

We point out again that we are aware of the fact that Nova Cygni 1992 was unique in the quality and completeness of the observations. Therefore, high-resolution spectral observations of more novae are required to illuminate the question of the origin of the knots.

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