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Hard emission from classical novae

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Abstract. — The thermonuclear model of classical novae has been very successful in explaining many observed features of novae. It also predicts unique γ-ray and X-ray signatures, a few of which possibly have already been observed. We describe recent developments in the expectations of these signatures and we discuss prospects for additional observations with current observatories.

Key words: nucleosythesis — novae — gamma-rays: theory — x-rays: stars.

1. Introduction.

The cause of classical nova outbursts is thought to be a thermonuclear runaway in a thin accreted envelope on a white dwarf in a binary system. The resulting high temperatures induce proton captures on most nuclei in the burning region, transforming stable seed nuclei into unstable proton-rich nuclei (β^+ emitters). These nuclei might be detectable via nuclear decay γ-ray or positron annihilation lines, either after the ejecta become thin to γ-rays (in a few days) or from the fraction of those nuclei convected to γ-ray thin regions during the outburst (e.g.,Clayton & Hoyle 1974). The small sizes and large luminosities of classical novae imply very high effective temperatures, and so they can also emit thermal X-rays. These hard emissions will ultimately provide very probing diagnostics of classical novae.

An excellent source of reviews of many aspects of classical novae is Bode & Evans (1989). A recent review of prospects for and attempts at observing γ-ray lines from novae is Leising (1991). Here we add a discussion of X-ray observations and classical novae spatial distributions, and we discuss recent developments including: new theoretical models of nova nucleosynthesis, suggestions that radioactive decay (of ^{22}Na) is responsible for the X-ray detections, and recent specific novae which might be studied in hard photons. We are compelled to mention, because it figures so prominently in this volume, that the very interesting transient X-ray source (unfortunately) designated Nova Muscae 1991 is *not* a classical nova at all, and is not relevant to the ideas mentioned here.

2. Nova calculations.

Peak temperatures of a few hundred million Kelvins, in addition to producing rapid nuclear reactions, cause very rapid convection in an envelope a few hundred kilometers thick. The convective timescale (10 to 100 sec) is comparable to the burning timescales of many of the important nuclear species. The temperature history of a given parcel of matter can be very complicated, so the resulting abundances can be quite different from what one would obtain by evolving the entire mass at the mean (or highest) temperature. Thus it is necessary to follow the dynamics of the explosion and the nuclear reactions in a coupled manner in nova calculations.

Starrfield *et al.* (1992) have begun to perform such calculations with a nuclear reaction network complete through calcium. Their calculations include proper treatments of the synthesis of ^{26}Al and ^{22}Na, both of which are interesting for γ-ray astronomy. Starrfield *et al.* (1992a) have modeled nova outbursts on 1.0, 1.25, and 1.35 $M_\odot$ O-Ne-Mg white dwarfs. They propose that it is such outbursts which produce the observed ^{26}Al, if indeed novae are its source, and which give rise to huge overabundances of Ne and other intermediate mass elements observed in some novae. These models each eject approximately $10^{-5} M_\odot$ of material with ^{26}Al mass fractions of 2%, 0.9%, and 0.7% respectively for the three white dwarf masses. The three models also eject ^{22}Na in abundances 5×10^{-5}, 2×10^{-3}, and 6×10^{-3} by mass, respectively.

Again the question arises: Can novae be the sole source of ^{26}Al in the interstellar medium? The γ-ray observations require that $\simeq 2 M_\odot$ of ^{26}Al have been ejected in the past mean lifetime, 1 million years. The amount ejected by novae can be estimated as:

$$M_{26Al}(\text{novae}) \simeq$$
$$0.4 M_\odot \left(\frac{R_{\text{O-Ne}}}{10\text{y}^{-1}}\right)\left(\frac{M_{\text{ej}}}{2\times10^{-5}M_\odot}\right)\left(\frac{X_{26}\text{Al}}{2\times10^{-3}}\right) \quad (1)$$

where $R_{\text{O-Ne}}$ is the rate of novae on O-Ne white dwarfs, M_{ej} is the average total mass ejected, and $X_{26\text{Al}}$ is the ejected mass fraction of ^{26}Al. This is formally smaller than the observed mass, but close enough given the uncertainties in all these numbers, that novae might be the source.

Current limits on the 1.275 MeV γ-ray flux from ^{22}Na limit the frequency of novae like the above 1.35 $M_\odot$ model ($X(^{22}\text{Na})=6\times10^{-3}$, $M_{\text{ej}}=10^{-5}M_\odot$) to about 10 yr^{-1} in the Galaxy. Because many novae might occur in lower mass systems, even the typical Ne-rich nova might eject far less ^{22}Na, and so these models are not contradicted by the observations.

Recent determinations of the ejected mass in the extremely neon-rich Nova Vulpeculae 1984 #2 (QU Vul) are as high as $M_{\text{ej}}=10^{-3}M_\odot$ (Saizar *et al.* 1992). Although no believable models of novae on O-Ne-Mg white dwarfs eject this much material, based on the recent calculations, we might expect $\sim 10^{-6}M_\odot$ of ^{22}Na to be ejected. However the *SMM* limit is $\leq 3\times10^{-7}M_\odot$ ^{22}Na from this object for a distance of 2 kpc. This limit would appear to conflict with the calculations, but clearly we must be careful about taking the models to represent an actual system which ejects 100 times as much mass as the models!

3. The galactic nova distribution.

Still the best hope for identifying the source of the ^{26}Al is the mapping of the spatial distribution of the emission (e.g.,, Leising & Clayton 1985.) Unfortunately, we have no good idea what the global Galactic nova distribution is. The sample of observed Galactic novae is woefully incomplete due to interstellar absorption and observational selection effects. To the extent we see them, the novae comprise an intermediate disk population, not unlike that of white dwarfs themselves. We can look to M31, where many novae have been observed, for a clue to how novae are distributed in a spiral galaxy. There the nova surface density tracks the surface brightness of the *bulge* very precisely (Ciardullo *et al.* 1987). Nova do *not* follow the total surface brightens of M31. In fact there is apparently no requirement for a disk population of novae in M31 at all. However, it seems clear that we do observe a disk component of novae in the Galaxy.

Previously used models of the Galactic nova distribution are all unsatisfactory. Models fit to the observed M31 novae, which are apparently extreme population II objects, in effect ignore the numerous disk novae which we observe. Models with only a disk or with nova surface density proportional to all light ignore the information provided by M31 novae. We currently see no completely satisfactory resolution to this problem. It might be that γ-ray observations, perhaps of ^{22}Na because it will be less ambiguous, will ultimately provide a map of where the Galactic nova are. At this meeting several speakers have offered model "nova" distributions as fits to the observed Galactic positron annihilation radiation. It is very unlikely that classical novae contribute much to this radiation. *Other than a possible contribution from ^{26}Al positrons, novae do not contribute significantly to the diffuse Galactic 511 keV radiation* (e.g.,, Leising *et al.* 1988; Leising & Clayton 1987).

4. X-ray emission from classical novae.

Soft X-ray emission is a natural consequence of the thermonuclear nova. Near the peak of the runaway the radius of the white dwarf envelope is $\leq 10^9$ cm and the luminosity is at or above the Eddington luminosity, so thermal X-rays will be emitted (for some tens of seconds.) Similarly, after the runaway a nearly constant luminosity nuclear shell source burns hydrogen at only a slightly lower luminosity (Starrfield *et al.* 1978; Fujimoto 1982) at a small radius. So when the ejecta become thin to soft X-rays (in one to a few months), novae should also be detectable sources at ≤ 1 keV. For example, a $10^{-5}M_\odot$ remnant envelope on a 1.0 $M_\odot$ white dwarf will have an effective temperature $T_{\text{eff}} \simeq 3\times10^5 K$. This will continue until the hydrogen of the envelope is substantially burned, which occurs on a timescale

$$t_{\text{nuc}} \simeq 20\left(\frac{M_{\text{H}}}{10^{-5}M_\odot}\right)\left(\frac{10^{38}\text{erg s}^{-1}}{L}\right) \text{ years,} \quad (2)$$

where M_{H} is the mass of hydrogen in the remnant envelope and L is the luminosity.

Novae have been observed at varying stages by EXOSAT (Ögelman *et al.* 1987). They detected three novae (Nova Muscae 1983, Novae Vul 1984 #1, and QU Vul) at times from 100 to 900 days after outburst. The X-ray flux from two novae is observed to rise over the first few hundred days, and the flux from the third is flat out to 800 days after which it declines. Older novae have not been observed by other experiments, so the decline is apparently common among novae. Ögelman *et al.* use the above relation to determine that the burned hydrogen mass is $M_{\text{H}} \sim 10^{-6}M_\odot$, which is quite small. Estimates of the white dwarf masses based on the maximum T_{eff} obtained from the X-ray observations are surprisingly small, 0.8 to 0.9 $M_\odot$. Attempts to model nova outbursts on white dwarfs of this mass have failed to yield observed nova characteristics.

The recent Nova Hercules 1991 was detected by ROSAT just 5 days after outburst (Predehl *et al.* 1991).

Although this nova was quite fast, it seems unlikely that the ejecta would be thin enough for soft X-rays from a remnant envelope to escape at such an early time. Perhaps an alternate explanation is required.

It has been suggested that the ~ 1 keV emission results from Compton scattering of 1.275 MeV photons from ^{22}Na (Starrfield *et al.* 1992b; see also Livio *et al.* 1992). This can be ruled out for several reasons. We estimate that the X-ray detections represent photon fluxes in the range 10^{-4} to 10^{-3} cm^{-2} s^{-1}. These would require that 10-100% of the 1.275 MeV γ-rays be scattered into a small band around 1 keV. This is prevented by the Compton kinematics; the scattered photons form a continuum starting at the line energy. Further, only the scattered photons can contribute to the continuum. Once the γ-ray mean-free-path becomes small only a small fraction of the decays contribute to the continuum at all. The time when the ejecta reach total γ-ray depth of unity is

$$t_\gamma \simeq 4\left(\frac{M_{\rm ej}}{10^{-4}M_\odot}\right)^{1/2}\left(\frac{1000\ {\rm km\ s}^{-1}}{v_{\rm exp}}\right)\ {\rm days} \qquad (3)$$

where $v_{\rm exp}$ is the mean expansion velocity, so the γ-ray photons scatter hardly at all after a few days. Finally, the photoelectric effect on the abundant intermediate mass atoms absorbs photons before they scatter enough times to reach 1 keV. No, the best way to detect ^{22}Na in novae is to observe the 1.275 MeV γ-rays directly.

5. Recent novae - N Her 1991 and N Cyg 1992.

Nova Hercules 1991 was discovered on 24 March 1991. This nova also has very strong neon emission lines and is a good candidate for Compton Observatory observations of ^{22}Na. Starrfield *et al.* (1992b) suggest that the 1.275 MeV flux from ^{22}Na is $\simeq 10^{-4}$ cm^{-2} s^{-1} for a distance of 3.4 kpc.

Nova Cyg 1992 was the brightest optical nova since 1975. We estimate, extrapolating to the time to decline by three magnitudes, that the distance to this nova is $\simeq 2$ kpc. The Compton Observatory OSSE just observed this nova during this meeting (March 1992). The hope is to detect either ^{7}Be (Clayton, 1981) or ^{22}Na, although only its relative proximity makes this nova a particularly interesting candidate at this time. This nova is also the best recent candidate for detecting the short-lived positron annihilation radiation and Compton continuum at the peak of the runaway. The BATSE is the most capable instrument in this regard (Fishman *et al.* 1991).

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