

**The early X-ray emission from V382 Velorum (=Nova Vel 1999):  
An internal shock model**

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## ABSTRACT

We present the results of *ASCA* and *RXTE* observations of the early X-ray emission from the classical nova V382 Velorum. Its *ASCA* spectrum was hard ( $kT \sim 10$  keV) with a strong ( $10^{23}$  cm $^{-2}$ ) intrinsic absorption. In the subsequent *RXTE* data, the spectra became softer both due to a declining temperature and a diminishing column. We argue that this places the X-ray emission interior to the outermost ejecta produced by V382 Vel in 1999, and therefore must have been the result of a shock internal to the nova ejecta. The weakness of the Fe K $\alpha$  lines probably indicates that the X-ray emitting plasmas are not in ionization equilibrium.

*Subject headings:* stars: individual (V382 Vel) — stars: novae, cataclysmic variables — X-rays: stars

### 1. Early X-ray Emission from Classical Novae

Classical novae (or simply, novae) are explosions caused by thermonuclear runaways on accreting white dwarfs (see, e.g., Chapter 5 of Warner (1995) for a review). In common with many other astrophysical explosions, a significant fraction of the energy goes into the kinetic energy of the ejecta: for an ejecta mass of  $10^{-4}M_{\odot}$  and an ejecta velocity of  $1.000$  km s $^{-1}$ , one obtains  $\sim 10^{45}$  ergs as the ejecta kinetic energy: these may be taken as typical values. Of course, not all novae are identical: “fast” novae are visually brighter at maximum, its visual light decays faster, and ejecta velocities are higher, than the “slow” novae. The fastness can be characterised by the time it takes the nova to decline by 2 ( $t_2$ ) or 3 ( $t_3$ ) visual magnitudes: there is a well-known correlation between the peak absolute magnitude and the rate of decline, which makes novae useful as distance indicators. The

white dwarf mass and other factors are known to influence the fastness of a nova, although full details are still being worked out. Another important distinction can be discerned from the abundances of the nova ejecta: roughly a third of recent novae are neon novae, those believed to occur on O-Ne-Mg white dwarfs, while the remainder are believed to occur on C-O white dwarfs.

The underlying binary is a cataclysmic variable (CV), that is, a white dwarf accreting from a late type companion, usually a Roche-lobe filling dwarf on or near the main sequence. Under certain conditions, the accreted material becomes degenerate; a sufficient accumulation of this fresh fuel causes a thermonuclear runaway. A nova typically reaches its peak visual brightness within a few days after the onset of brightening. In the early decay phase, the intense wind from the still nuclear-burning white dwarf creates a huge pseudo-photosphere, completely obscuring the underlying binary. The declining mass-loss rate shrinks the photosphere, during which the bolometric luminosity remains roughly constant, at about the Eddington limit, and the effective temperature increases. Finally, when the photosphere has shrunk to the original radius of the white dwarf, the nova may become a super-soft source, exhibiting an intense, optically thick radiation from the white dwarf surface, with an effective temperature of the order 50 eV. Such super-soft emission is observed 6 months to several years after the visual peak of the nova.

In addition, an early, hard X-ray component has been observed in several recent novae. V838 Herculis (=Nova Herculis 1991,  $V_{\text{peak}} \sim 5.0$ ) was detected 5 days past optical maximum at  $0.16 \text{ ct s}^{-1}$  in *ROSAT* PSPC (Lloyd et al 1992). V1974 Cygni (=Nova Cygni 1992,  $V_{\text{peak}} \sim 4.2$ ) was detected 60 days past maximum at  $0.02 \text{ ct s}^{-1}$  in *ROSAT* PSPC (Balman et al 1998). Nova Scorpii 1997 ( $V_{\text{peak}} \sim 9$ ) was detected  $\sim 100$  days past maximum at  $0.07$  and  $0.02 \text{ ct s}^{-1}$  respectively in *BeppoSAX* LECS and MECS (Orio et al 1997). Finally, the *ROSAT* PSPC detection of V351 Puppis (=Nova Puppis 1991) 16 months after

the visual maximum, at  $0.223 \text{ ct s}^{-1}$  may also be due to the same component (Orion et al 1996).

In this paper, we report on the results of an *ASCA* Target-of-opportunity (TOO) observation and an *RXTE* monitoring campaign of the early, hard X-ray emission from V382 Vel. Observations are described in §2, results are presented in §3 and interpreted in §4.

## 2. Observations

V382 Velorum (=Nova Velorum 1999) was discovered on 1999 May 22 at  $V \sim 3$ . The pre-discovery photographs extend the detection back to May 20.923 UT at magnitude 7.0–7.25; the nova was undetected at May 20.57 to a limiting magnitude of  $\sim 13$ . We estimate that peak of thermonuclear runaway, initial ejection of mass, and the beginning of visual brightening all occurred around 1999 May 20.5 (=JD 2451319.0); we will refer to this as time 0 of this nova in this paper. Given the rapid rise, this estimate is probably accurate to better than a day, which is adequate for our purposes.

V382 Vel appeared to have peaked near  $m_v \sim 2.8$  at about day 2.0, making this the brightest nova since V1500 Cygni (=Nova Cygni 1975), and declined rapidly. In Fig. 1, we have plotted the visual magnitude estimates of V382 Vel as published in various IAU Circulars (nos. 7176, 7177, 7179, 7184, 7193, 7203, 7209, 7236, and 7238), since they provide the best overall coverage throughout the first 3 months of the nova. We have supplemented these with magnitude estimates from pre-discovery photographic plates, and with photometry at Mt. John University observatory (Kilmartin (1999) and Gilmore (1999)) between Jun 26 and Jul 14 (a period for which no visual magnitude estimates are available in IAU's), although there may well be an offset between visual magnitudes and

photographic or photoelectric measurements. V382 Vel is a very fast nova: Della Valle et al (1999) have measured the rate of decline of the nova to be  $t_2=6$  days and  $t_3=10$  days, and hence estimated a peak absolute visual magnitude  $M_V$  of  $-8.7 \pm 0.2$ : this implies a distance to the nova of about 2 kpc. It is also a neon nova (Woodward et al 1999), as evidenced by the detection of strong [NeII]  $12.81\mu$  line.

The rare brightness of the nova (the brightest since the advent of imaging X-ray astronomy) has made V382 Vel a prime target for X-ray observations. Accordingly, by the end of 1999, V382 Vel has been observed with *RXTE* (5 times), *BeppoSAX* (twice), *ASCA* (once) and *Chandra* (once). Here we concentrate on the *RXTE* and *ASCA* data (summarized in Table 1; see also Fig. 1). We also cite the published results of the *BeppoSAX* observations (Orio et al (1999a) and Orio et al (1999b)).

The *ASCA* observation (see also the preliminary report by Mukai & Ishida (1999)) was performed between 1999 June 9 13:09 UT and June 10 16:01 UT, for approximately 40 ksec on-source. We have performed standard data screening and extraction, and combined the data from 2 pairs of similar instruments for spectroscopic analysis (i.e., producing one SIS spectrum and one GIS spectrum, each with an associated response and a background file). For our light curve analysis, we have combined the data from all 4 instruments.

There have been 5 public TOO observations of V382 Vel with *RXTE*, from which we have only analyzed the PCA data (a simple extrapolation of PCA spectral model would argue against a HEXTE detection; even if a hard X-ray source was to be detected, we cannot be confident of its true origin). All were performed with Epoch 4 gain setting, with varying number of Proportional Counter Units (PCUs) on (see Table 1), obtaining usable data of V382 Vel for 0.7-2.4 ksec per visit. In addition, during the middle of observation2, a raster scan was performed to confirm that V382 Vel is the only source of hard X-rays in this area of the sky. We have used the faint source model for background subtraction

(specifically, `pca_bkgd_faint17_e04v03.mdl` and `pca_bgd_faint240_e04e03.mdl` in addition to `pca_saa_history`). We have used responses created by `pcarmf v7.01` for spectral fitting.

### 3. Results

#### 3.1. First *RXTE* observation

This observation was performed at day 5.7 in our convention, or only about 3 days past the visual maximum. Had a secure detection been obtained, this would have been the earliest hard X-ray detection of a classical nova. However, this was not the case, as has been reported earlier (Mukai & Swank 1999). Even though there is a statistically significant count excess over the background model in the 2.5–10 keV band (our refined value is  $0.11 \pm 0.03$  ct s<sup>-1</sup> per PCU), this cannot be considered a secure detection, given the point-to-point fluctuation in the cosmic X-ray background, particularly at such a low Galactic latitude ( $b^{II} = 5.8^\circ$ ). A 0.2 ct s<sup>-1</sup> per PCU source cannot be excluded, roughly corresponding to  $2.5 \times 10^{-12}$  ergs cm<sup>-2</sup>s<sup>-1</sup> in the 2–10 keV band.

#### 3.2. *ASCA* data

The imaging capability of *ASCA* leaves no doubt that V382 Vel was strongly detected on day 20.5 (see also Orio et al (1999a) for the slightly earlier, and equally secure, detection by *BeppoSAX*).

The combined 64-s bin light curve was analyzed for variability. The best straight-line fit has a positive slope (combined count rates increasing from 0.564 ct s<sup>-1</sup> to 0.583 ct s<sup>-1</sup> during our  $\sim 1$  day observation), i.e., increasing with a timescale of  $\sim 30$  days at day 20.5.

This fit has a  $\chi^2_\nu$  of 1.15 for 626 degrees of freedom, implying that the source was variable on a shorter timescale formally at a 99.4% confidence level. However, a Fourier analysis reveals no significant periodicity, to a limiting amplitude of  $\sim 5\%$ , and the apparent variability at this level may well be due to imperfect background subtraction and other instrumental effects.

We have fitted the GIS and SIS spectra of V382 Vel with a Bremsstrahlung continuum model (Fig. 2). The choice of this model was dictated by a combination of physical considerations and the quality of the fits, not only of this observation but of the later *RXTE* data as well. We find that a single-component Bremsstrahlung model with a uniform absorber gives a poor fit, with excesses at low energies. A partial-covering absorber model results in a marked improvement to the fit: the absorbing column is found to be  $1.01 \pm 0.05 \times 10^{23} \text{ cm}^{-2}$ , with a covering fraction of 99.5%. The bremsstrahlung model has a temperature of  $kT = 10.2^{+2.0}_{-1.7} \text{ keV}$ . There is a weak detection a Fe K line at  $6.63 \pm 0.11 \text{ keV}$  with an equivalent width of  $130^{+30}_{-70} \text{ eV}$ . We have also attempted fitting the *ASCA* spectra with the *mekal* plasma emission model. Since the continuum temperature is such that strong 6.7 and 6.97 keV Fe K lines are expected, the fit fails unless the abundances are allowed to vary; in this case, the abundance of Fe (the only element the *ASCA* data are sensitive to) of less than 10% Solar is indicated. The observed flux is  $2.13 \times 10^{-11} \text{ ergs s}^{-1} \text{ cm}^{-2}$  and inferred luminosity (corrected for absorption and for an assumed distance of 2 kpc) is  $4.5 \times 10^{34} \text{ ergs s}^{-1}$ . The inferred emission measure (EM) is  $1.7 \times 10^{57} \text{ cm}^{-3}$ .

### 3.3. Follow-up *RXTE* observations: Spectral Evolution

During the subsequent *RXTE* campaign, V382 Vel was strongly detected, and showed a marked softening from the *ASCA* observation (day 20.5) to the last *RXTE* observation (day 59). The spectra are shown in in Fig. 3.

For these *RXTE* spectra, we have used a simple absorber model, since *RXTE* PCA is not sensitive to the type of soft excess seen in the *ASCA* spectrum. The column densities deduced from the fits decrease to an almost undetectable (to *RXTE*) level, accompanied by a decrease in the temperature of the bremsstrahlung model: either change in itself is not sufficient to explain the observed spectral softening. The Fe K line is securely detected above the bremsstrahlung continuum model in observations 2 & 3. However, even then, the lines are weaker than the plasma models would suggest.

These results are summarized in Table 2 and in Fig. 4.

#### 4. Discussion

CVs long after a nova eruption are often seen as X-ray sources with luminosities in the  $10^{30}$ – $10^{34}$  ergs  $s^{-1}$  range. However, it is unlikely that accretion can explain the X-rays we observed in V382 Vel, given that the underlying binary was buried deep within the optically thick wind at the epochs of these observations, quite apart from the question of whether accretion could have been reestablished within several weeks of the onset of the nova eruption.

Three nova-specific mechanisms for hard X-ray emission have been proposed: radioactive decays, super-soft emission, and shock emission. Radioactive decays of  $^{22}\text{Na}$  produces 1.275 MeV  $\gamma$ -ray line, which could produce X-rays via Compton-degradation (Livio et al 1992). However, resulting X-rays predominantly originate from a surface with Compton optical depth  $\sim 1$ , i.e.,  $N_{\text{H}} \sim 10^{24}$   $\text{cm}^{-2}$ ; this is far in excess of even the highest column density seen in V382 Vel,  $\sim 1.0 \times 10^{23}$   $\text{cm}^{-2}$  measured with *ASCA*, hence we exclude radioactive decays from further considerations. The super-soft emission is the optically thick radiation from the white dwarf surface, with an effective temperature of the order

50 eV, thus clearly of the wrong shape to explain our observations. This component was, however, observed with *BeppoSAX* in November, 1999 in V382 Vel (Orio et al (1999b)).

This leaves shock emission as the only viable candidate as the origin of X-rays from V382 Vel observed with *ASCA* and *RXTE* between day 20.5 and 59.

#### 4.1. External Shock Model

In one version of the shock model (see, e.g., Lloyd et al (1992)), the nova ejecta interact with pre-existing, circumstellar material. There is a severe problem with such an external shock model: there isn't enough circumstellar material around a classical nova. To show that this is the case, we will compare nova remnants with the much better studied supernova remnants (see, e.g., Lozinskaya (1992)). The first stage in the evolution of a supernova remnant (and, presumably, of a nova remnant) is the free expansion phase, when the swept-up interstellar medium (ISM) or circumstellar mass is much less than that of the ejecta. During this phase, the expansion does not slow down and only a small fraction the kinetic energy is converted to thermal energy (and subsequently radiated as X-rays). In the next (Sedov) phase, the deceleration is noticeable, and a significant shock heating occurs, converting kinetic to thermal energies. The approximate boundary between these two stages is obtained by equating the swept-up mass with the ejecta mass. For an ejecta mass of  $10^{-4} M_{\odot}$ , and an ISM density of  $0.1 \text{ cm}^{-3}$ , the ejecta must reach a radius of  $\sim 0.2$  pc, which would take  $\sim 200$  years for an ejecta velocity of  $1000 \text{ km s}^{-1}$ . At the point 20 days after onset, the swept-up ISM mass would be roughly 10 orders of magnitude smaller than the ejecta mass, and even the total kinetic energy imparted onto the swept-up ISM is of the order of  $2 \times 10^{34}$  ergs. Even allowing for generous errors in this analysis, it is highly improbable for the nova ejecta to have encountered enough ISM for a detectable external shock.

It might seem that, even if ISM is insufficient, we could invoke a circum-binary material to save the external shock model. It is indeed conceivable for the pre-nova binary to have lost a significant amount of mass. However, mass loss from CVs tend to occur as winds at near the white dwarf escape velocities, thus it is unlikely for the lost mass to remain in close proximity to form a dense circum-binary shell. If the mass donor is an M giant, as is the case in several recurrent novae, there would be a dense, slow wind against which the nova ejecta might produce an external shock; there is no indication, however, that V382 Vel possesses a giant secondary.

Finally, and most convincingly, nova shells, the optical nebulosity associated with the ejecta, are commonly observed decades after the eruptions in nearby novae. The shell around DQ Her (Nova Herculis 1934), for example, has suffered little (if any) deceleration more than 40 years after the eruption (Herbig & Smak 1992). Clearly, the ejecta of DQ Her has been expanding almost freely into a low-density ISM. If the studies of expansion parallaxes of classical novae (e.g., Cohen (1985)) are to be believed, free expansion is the rule rather than the exception. This would indicate that any external shocks, capable of producing X-rays, do not exist yet in typical nova shells, observed a few years to many decades after their eruptions.

We therefore discard the external shock explanation for the early X-ray emissions in classical (non-recurrent) novae.

#### 4.2. Internal Shock Model

The *ASCA* and *RXTE* observations reported here provide three valuable clues as to the nature of the putative shock: the  $N_H$  history, the kT history, and the behavior of the Fe K line.

The observed  $N_{\text{H}}$  cannot be interstellar, because it is variable. Moreover, the UV observations (Shore et al 1999) indicate a reddening  $E_{\text{B-V}}$  of perhaps 0.2, or  $N_{\text{H}} \sim 3 \times 10^{21} \text{ cm}^{-2}$ . This is also consistent with the November, 1999, *BeppoSAX* observation, from which an X-ray column of  $N_{\text{H}} = 2 \times 10^{21} \text{ cm}^{-2}$  has been determined (Orio et al 1999b).

A simple model consisting of a discrete shell of mass  $5 \times 10^{-5} M_{\odot}$  expanding at  $1000 \text{ km s}^{-1}$ , ejected at time 0 (the presumed peak of the thermonuclear runaway), is successful in describing the time history of  $N_{\text{H}}$  as measured with *RXTE* if one assumes a point-like X-ray source at its center. For an extended source, photons from near the limb has longer path lengths through the cold outer shell, thus the above shell mass is an overestimate, particularly for a limb-brightened X-ray source. The point-source model that fits the *RXTE* observation overpredicts the *ASCA*  $N_{\text{H}}$  by 50%. This may be due, in part, to the simplistic treatment of the complex geometry; or the outer shell may have been partially ionized at early stages, allowing low energy photons to escape and hence complicating our spectral fits (a similar mechanism may have allowed the very early detection of V838 Her with *ROSAT* (Lloyd et al 1992)). Extrapolation of this model back to day 5.7, the epoch of the initial *RXTE* observation, implies that the column would have been  $\sim 2 \times 10^{24} \text{ cm}^{-2}$ , too high to allow X-rays escape even allowing for some overprediction. That is, the  $N_{\text{H}}$  history is suggestive of an origin in an expanding shell, the ejecta from the 1999 nova eruption itself. The mass in this shell is probably much less than  $5 \times 10^{-5} M_{\odot}$  if, as seems likely, the X-ray emission is from a limb-brightened inner shell.

This model of the  $N_{\text{H}}$  history leads naturally to an internal shock model. An expanding outer shell provides the observed  $N_{\text{H}}$ , with the X-ray producing shock residing inside. The simplest model, then, consists of two distinct shells of nova ejecta. The initial ejecta provide the absorbing column: a layer of later, and faster-moving, ejecta plough into the initial ejecta. The high shock temperature of  $kT \sim 10 \text{ keV}$  requires a strong shock with velocity

differential of  $\sim 3000 \text{ km s}^{-1}$ . Later observations show a softer spectrum, in  $kT$  as well as in  $N_H$ , which suggests that the two sets of ejecta are merging to form a single layer.

This suggestion has similarities to the interacting winds model developed to explain *ROSAT* observations of V838 Her (O'Brien et al 1994). However, the wind speed in their model increases smoothly with time; it is not clear if this could produce a temperature as high as  $kT \sim 10 \text{ keV}$ , which more likely indicates a sharp discontinuity in velocity. A closer similarity exist between our model and that of Friedjung (1987), which was motivated by the vast literature on the optical spectra of classical novae in eruption.

Quantitative models of optical spectra of classical novae are generally based on a single-component, optically thick wind approximation (Bath & Shaviv 1976). However useful this formalism may be, it is clear from the rich taxonomy of optical spectra of novae (summarized most notably by Payne-Gaposchkin (1957)) that nova ejecta are far more complex than this. Several distinct systems are often recognized. In time order, these are called pre-maximum, principal, diffuse enhanced, and Orion components. As the name implies, the pre-maximum component is the first absorption features seen, before the visual light curve reaches its maximum; their typical velocities are in the  $100\text{--}1000 \text{ km s}^{-1}$  range. This component therefore is associated with the initial ejecta from the nova eruption, which presumably carries the pseudo-photosphere with it as it expands. The principal system follows next, with a higher velocity and a higher ionization; this is the system that persists decades after the eruptions and can be identified with the expansion velocity of the nova shells. Diffuse enhanced and Orion systems are yet of higher ionizations and higher velocities ( $1000 \text{ km s}^{-1}$  in slow nova to as high as  $4000 \text{ km s}^{-1}$  in very fast novae).

We see ever deeper into the optically thick wind as time goes by, due to the decrease in the mass loss rate, hence the optical depth at a given physical location. This does explain the increasing trend in ionization; however, we should observe less accelerated material as

time goes on in a one-zone wind model. The fact that the observed velocities increase with time probably requires at least two distinct components. For example, Friedjung (1987) explains the principal component as due to the result of a collision between the slow-moving pre-maximum system with the faster-moving diffuse enhanced/Orion system. Applied to V382 Vel, a fast nova, this model predicts a collision between the  $1000 \text{ km s}^{-1}$  pre-maximum component and the  $4000 \text{ km s}^{-1}$  fast wind, with the resulting shock of  $kT \sim 10 \text{ keV}$ , just as observed.

In more theoretical terms, the pre-maximum system can be associated with the dynamical ejection of the white dwarf envelop at near the peak of the thermonuclear runaway: the faster materials can then be associated with radiation-driven wind due to the continued shell hydrogen burning, whose other manifestation is the super-soft X-ray emission from the hot photosphere to be observed several month later.

Assuming that the shock is due to the collision between the pre-maximum system and a fast-moving wind, what are the likely physical conditions? First, the density of the pre-maximum ejecta can be estimated as follows. Let us assume an ejecta mass of  $2 \times 10^{-5} M_{\odot}$  (as we have argued that the  $5 \times 10^{-5} M_{\odot}$  figure from  $N_{\text{H}}$  history was likely an upper limit). The ejecta are expanding as a shell with radius  $v_{\text{pm}}T$ , where  $v_{\text{pm}}$  is the ejection velocity  $\sim 1000 \text{ km s}^{-1}$  and  $T$  the time since explosion. There is likely to be a velocity dispersion  $\Delta v$  (say,  $200 \text{ km s}^{-1}$ ) in the ejecta: taking the increasing radial spread into account, the volume of the pre-maximum system at 20 days after eruption is  $\sim 1.6 \times 10^{43} \text{ cm}^3$  and the density is estimated to be  $7.5 \times 10^8 \text{ cm}^{-3}$ .

For the fast wind, since we assume this to be a continuous (and slowly changing) phenomenon, velocity dispersions would not affect the density. For a wind mass loss rate of  $2 \times 10^{22} \text{ g s}^{-1}$  (or  $\sim 10^{-4} M_{\odot}$  in 100 days) at a wind velocity of  $4000 \text{ km s}^{-1}$ , the wind density at the pre-maximum shell would be  $7.5 \times 10^7 \text{ cm}^{-3}$ . It appears likely that the fast

wind will be initially assimilated into the pre-maximum shell, after undergoing a shock, with a post-shock density of the order  $3 \times 10^8 \text{ cm}^{-3}$ .

If our interpretation is correct, the physical conditions of the early X-ray emission source in V382 Vel is orders of magnitudes denser than in supernova remnants, and orders of magnitudes more rarified than in accretion shocks in CVs, two well-studied classes of shock heated, X-ray emitting, plasmas. Although it may be comparable to stellar coronae in density alone, the heating mechanism and the environment are different. Applications of existing spectral models (widely tested in supernova remnants and stellar coronae) must therefore proceed with caution.

#### 4.3. Weak Fe K Lines: Underabundant or Underionized?

The weakness of the Fe K line is consistent with the shock model, provided either that the Fe abundance is low in the ejecta, or that the shocked plasma is not in ionization equilibrium.

There is no theoretical objection to a low Fe abundance in nova ejecta. This could arise either because the white dwarf accretes low Fe abundance material from the secondary, or because the heavy elements have settled down to deeper layers of the primary in before the nova eruption. However, V382 Vel has been classified as a Fe II nova, because its optical spectra include strong and broad Fe II lines (Steiner et al (1999), Della Valle et al (1999)). In addition, the X-ray continuum shape in the 5–10 keV region measured with ASCA suggest the presence of an Fe edge at a level consistent with a Solar composition absorber with  $N_{\text{H}} \sim 10^{23} \text{ cm}^{-2}$  (NB this is not a secure result on its own, as the Fe edge depth is linked with the Fe emission line strength and the continuum shape in our fit). Clearly, Fe is present in the ejecta of V382 Vel. Therefore, we prefer to discount a low abundance as the

explanation for the weak Fe K features in the X-ray spectra.

Instead, we consider it likely that the Fe in the nova ejecta is underionized. Studies of supernova remnants typically find that the ionization equilibrium is archived with a timescale  $t$  such that  $nt \sim 10^{12} \text{ cm}^{-3}\text{s}$  (e.g., Masai (1994)). In young supernova remnants with  $nt < 10^{12} \text{ cm}^{-3}\text{s}$ , the iron atoms are in the process of being ionized and this can result in weaker Fe K $\alpha$  line at an energy somewhat lower than at equilibrium. We do not have a detailed model of how this might apply to V382 Vel, and it may not be wise to apply the existing non-equilibrium models of supernova remnants without carefully considering the different conditions.

One observational constraint we have on the density is the emission measure, which can be derived from the normalization of the bremsstrahlung model: they are  $1.7 \times 10^{57} \text{ cm}^{-3}$  for the *ASCA* data and  $\sim 6 \times 10^{57} \text{ cm}^{-3}$  for the subsequent *RXTE* spectra. If the emission region of volume  $V$  has a uniform density  $n$ , emission measure simply equals  $n^2V$ . We can calculate the minimum density consistent with the observed X-ray spectrum by taking the volume of the sphere within the  $1000 \text{ km s}^{-1}$  pre-maximum ejecta front at day 20 ( $\sim 2 \times 10^{43} \text{ cm}^3$ ), and assuming a filling factor of 1/4 (since a strong shock compresses by a factor of 4): it is  $\sim 2 \times 10^7 \text{ cm}^{-3}$  (for the assumed 2 kpc distance). Such a plasma will stay in nonequilibrium for  $\sim$ half a day. This short timescale for reaching ionization equilibrium is a problem for this interpretation: perhaps the observed X-ray emissions are dominated by recently shocked materials. On the positive side, there is a hint that the detected lines were at lower energies than those predicted by the ionization-equilibrium plasma models (Table 2 and Fig. 4), which is predicted by the non-equilibrium models. Clearly, we need higher quality observations of future bright novae, as well as further modelling of nova ejecta, to discover for certain the cause of weak Fe K $\alpha$  lines in V382 Vel.

## 5. Conclusions

We have observed early X-ray emission from a bright classical nova, V382 Vel. The X-ray spectrum was hard with  $kT \sim 10$  keV and  $N_H = 1 \times 10^{23} \text{ cm}^{-2}$  3 weeks after the onset of the eruption, declining to 2.5 keV and  $2 \times 10^{22} \text{ cm}^{-2}$  2 months after the peak in the optical. This evolving hard X-ray emission can be best modelled as due to an internal shock within the nova ejecta, as postulated by Friedjung (1987).

Sensitive X-ray observations of other bright novae are necessary to clarify the dependence of hard X-ray properties on the speed class. However, slower novae will almost certainly have a lower peak temperature and remain obscured for a longer period. Frequent optical spectroscopy is also necessary to obtain the velocities of various ejecta components, to be compared with the X-ray temperature evolution.

Given an assumed distance of 2 kpc, V382 Vel maintained an X-ray luminosity of  $7.5 \times 10^{34} \text{ ergs s}^{-1}$  for at least 20, perhaps as long as 40, days. The fluence in the X-ray component during this interval was about  $2 \times 10^{41}$  ergs, a small fraction of the estimated total kinetic energy of the ejecta. This is consistent with the apparent free expansion of the nova shells observed decades after eruptions, and re-enforces the notion that, if nova ejecta-ISM interaction produces X-rays, it happens many decades after the eruption.

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Fig. 1.— The visual light curve of V382 Vel (crosses), augmented by magnitudes estimated from pre-discovery photographic plates (an arrow indicating an upper limit of magnitude 13, and diamonds indicating detections) and Mt. John University Observatory photometry (open squares). The times of X-ray observations that we report in this paper are labeled with an “A” for the *ASCA* observation and by numbers for the *RXTE* monitoring campaign.

Fig. 2.— The *ASCA* spectra of V382 Vel. GIS data (average of GIS-2 and GIS-3) are plotted as crosses, and SIS data (SIS-0 and SIS-1 average) as diamonds, in the upper panel, also with the best-fit bremsstrahlung model with a simple absorber. In the bottom panel, the residuals are shown in the form of data/model ratios. A large soft excess against this simple absorber model is clearly seen. Also apparent is the hardness of the intrinsic emission. A weak Fe K line is also visible in the upper panel.

Fig. 3.— The *RXTE* spectra of V382 Vel. The data from the four observations in which V382 Vel was detected are plotted using different symbols. The histogram indicates the best-fit model from the *ASCA* observation convolved with the *RXTE* PCA response.

Fig. 4.— The results of spectral fits of V382 Vel. From top to bottom, the column density, the bremsstrahlung temperature, the Fe K line energy shift relative to the plasma model prediction for the appropriate continuum temperature, the observed-to-predicted equivalent width ratio of the Fe K line, and the inferred total luminosity for  $d=2\text{kpc}$ , are shown, as functions of time since eruption. On the top panel, the prediction of a simple  $5.0 \times 10^{-5}$  (solid) and  $3.2 \times 10^{-5}$  (dotted)  $M_{\odot}$  shell models are also shown.

Table 1. RXTE and ASCA Observations of V382 Velorum.

Date	Satellite <sup>a</sup>	Exposure (ksec) <sup>b</sup>	Count Rate <sup>c</sup>
1999 May 26 (day 5.7)	<i>RXTE</i> (0123)	2.4	0.11±0.03
1999 Jun 9/10 (day 20.5)	<i>ASCA</i>	33.6/39.5	0.161±0.002/0.140±0.002
1999 Jun 20 (day 31)	<i>RXTE</i> (02) <sup>d</sup>	1.3	3.59±0.06
1999 Jun 24 (day 35)	<i>RXTE</i> (0123)	0.7	3.24±0.06
1999 Jul 9 (day 50)	<i>RXTE</i> (023)	2.1	2.94±0.04
1999 Jul 18 (day 59)	<i>RXTE</i> (123)	1.0	2.01±0.06

<sup>a</sup>For *RXTE* observations, the PCUs that were used for the observations are indicated in parentheses.

<sup>b</sup>Good on-source time after standard screening. For the *ASCA* observation, exposures for GIS and SIS are shown.

<sup>c</sup>For the *RXTE* observations, 2.5–10 keV count rates per PCU are shown; for the *ASCA* observation, the average GIS rate and the average SIS rate are shown.

<sup>d</sup>This observation included a scan to confirm that the nova was the only source of hard X-rays.

Table 2. Results of Spectral Fits.

Day	$N_{\text{H}}$ ( $10^{22} \text{ cm}^{-2}$ )	kT (keV)	Line E (keV)	Line EqW (eV)	Luminosity ( $\text{erg s}^{-1}$ )	EM ( $\text{cm}^{-3}$ )
20.5	$10.1 \pm 0.5$	$10.2^{+2.0}_{-0.7}$	$6.63 \pm 0.11$	$130^{+30}_{-70}$	$4.5 \times 10^{34}$	$1.7 \times 10^{57}$
31	$7.7 \pm 2.0$	$4.0^{+0.8}_{-0.6}$	$6.2^{+0.2}_{-0.3}$	$190^{+120}_{-105}$	$7.9 \times 10^{34}$	$6.3 \times 10^{57}$
35	$6.0 \pm 1.9$	$3.5^{+0.7}_{-0.6}$	$6.4 \pm 0.4$	$220 \pm 150$	$7.2 \times 10^{34}$	$5.6 \times 10^{57}$
50	$3.1 \pm 1.2$	$2.5 \pm 0.3$	$7.1^{+0.6}_{-0.9}$	$220^{+230}_{-110}$	$7.6 \times 10^{34}$	$5.9 \times 10^{57}$
59	$1.7^{+2.4}_{-1.7}$	$2.4^{+0.6}_{-0.4}$			$4.9 \times 10^{34}$	$4.0 \times 10^{57}$



Fig 1

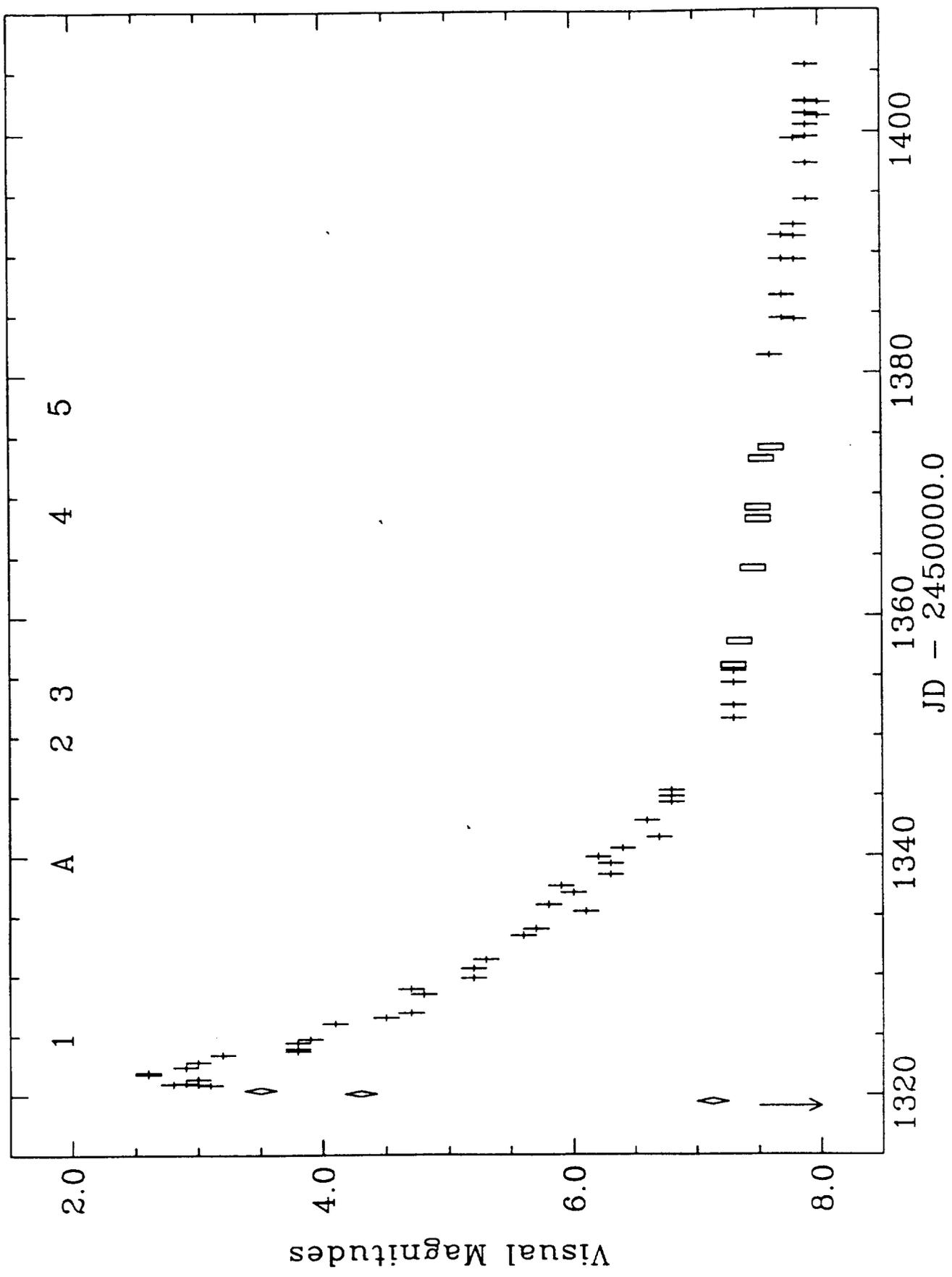


Fig 2

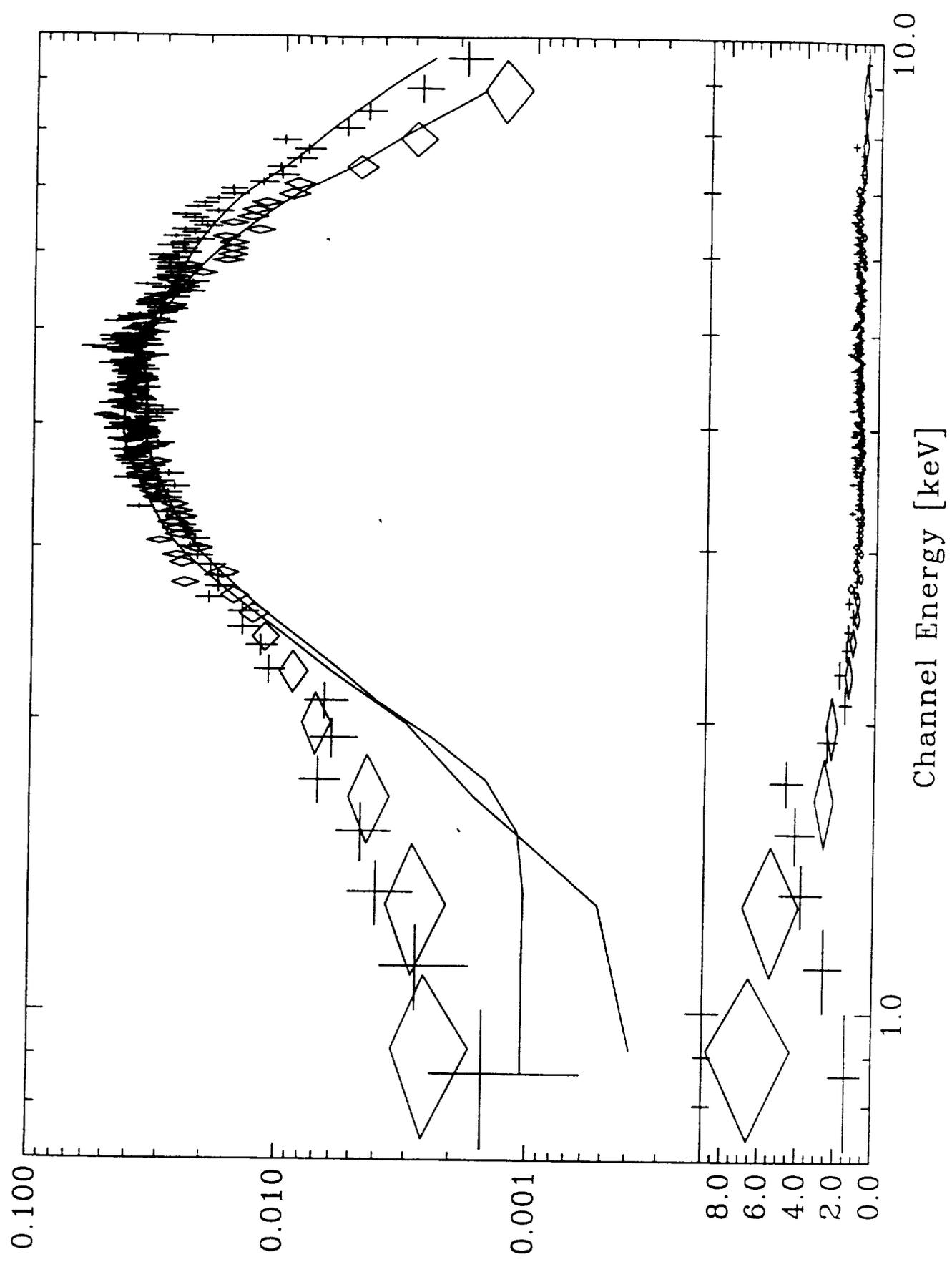


Fig 3

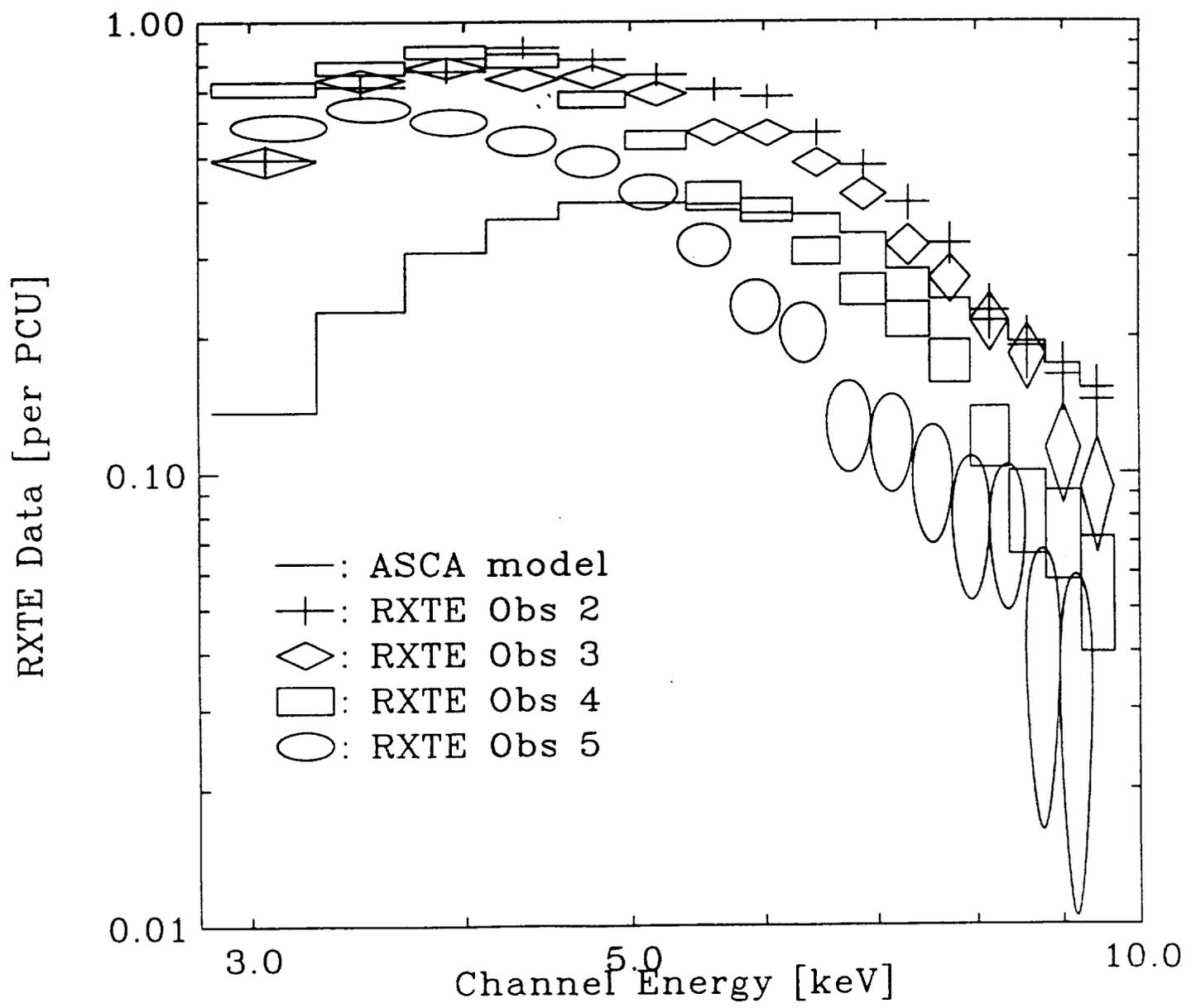


Fig 4

