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The X-ray emission from Nova V382 Velorum – I. The hard component observed with *BeppoSAX*

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ABSTRACT

We present *BeppoSAX* observations of Nova Velorum 1999 (V382 Vel), carried out in a broad X-ray band covering 0.1–300 keV only 15 d after the discovery and again after 6 months. The nova was detected at day 15 with the *BeppoSAX* instruments which measured a flux $F_x \simeq 1.8 \times 10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ in the 0.1–10 keV range and a 2σ upper limit $F_x < 6.7 \times 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ in the 15–60 keV range. We attribute the emission to shocked nebular ejecta at a plasma temperature $kT \simeq 6$ keV. At six months no bright component emerged in the 15–60 keV range, but a bright central supersoft X-ray source appeared. The hot nebular component previously detected had cooled to a plasma temperature $kT < 1$ keV. There was strong intrinsic absorption of the ejecta in the first observation and not in the second, because the column density of neutral hydrogen decreased from $N(\mathrm{H}) \simeq 1.7 \times 10^{23}$ to $N(\mathrm{H}) \simeq 10^{21}\,\mathrm{cm^{-2}}$ (close to the interstellar value). The *unabsorbed* X-ray flux also decreased from $F_x = 4.3 \times 10^{-11}$ to $F_x \simeq 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$.

Key words: stars: individual: V382 Vel – novae, cataclysmic variables – X-rays: stars.

1 INTRODUCTION

Nova Velorum 1999 (V382 Vel) was discovered in outburst on 1999 May 22 (Williams & Gilmore 1999). It was the second brightest nova in this half of the century ($V = 2.6$; Seargent & Pearce 1999) and a 'O–Ne–Mg nova' (Shore et al. 1999a,b). In terms of the time to decay from visual maximum by 2 and 3 mag (see Della Valle & Livio 1995) it was a 'fast' nova, with $t_2 = 6$ d and $t_3 = 10$ d (Della Valle, Pasquini & Williams 1999). The peak ejection velocity v_{ej} inferred from the emission lines was $v_{\mathrm{ej}} \simeq 4000\,\mathrm{km\,s^{-1}}$ (Shore et al. 1999a). The estimated distance is 2 kpc (Della Valle et al. 1999).

The nova was declared a Target of Opportunity by the *BeppoSAX* Mission Scientist. The *BeppoSAX* X-ray satellite carries instruments that cover the energy range 0.1–300 keV. We present results from the coaligned Low-Energy Concentrator Spectrometer (LECS; 0.1–10 keV; Parmar et al. 1997), the Medium-Energy Concentrator Spectrometer (MECS; 1.8–10 keV; Boella et al. 1997), and the Phoswich Detection System (PDS; 15–300 keV; Frontera et al. 1991). The LECS and the MECS consist of grazing incidence telescopes with imaging gas-scintillation proportional counters in their focal planes. The non-imaging PDS consists of four independent units arranged in pairs each having a separate collimator, alternatively rocked on- and off-source during the observation.

Classical and recurrent novae are expected to emit X-rays in an outburst via three different mechanisms. Luminous 'supersoft' X-ray emission of the central source is thought to indicate that the white dwarf is still burning hydrogen in a shell (e.g. V1974 Cyg, Krautter et al. 1996; or N LMC 1995, Orio & Greiner 1999). This is important because if all the accreted envelope is not ejected the white dwarf mass increases, after repeated outbursts.

Shocks are not the main mechanism of nova outbursts: usually the mass outflow is not due to a 'detonation' but due to a radiatively driven super-wind (Bath & Shaviv 1976). However, shocks on a small scale, arising from complex phenomena in the nova wind or in the interaction between the ejecta and the circumstellar medium, are likely to be frequent. The recurrent nova RS Oph, and novae

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V838 Her (N Her 1991), V351 Pup (N Pup 1991), V1974 Cyg (N Cyg 1992) and probably LMC 1992 were hard X-ray sources shortly after the outburst. Thermal bremsstrahlung models with temperatures in the range 0.5–20 keV and luminosities 10^{33-34} erg s^{-1} fit the data. A list of references includes Mason et al. (1987), Lloyd et al. (1992), Orio et al. (1996), Balman, Krautter & Ögelman (1998) and Orio, Covington & Ögelman (2000). This information is largely based on the *ROSAT* data, and only in the energy range 0.2–2.4 keV. Only V838 Her was observed as early as 9 d after maximum. There are indications that the plasma temperature might have been much higher than the *ROSAT* range (e.g. Lloyd et al. 1992).

A third mechanism of X-ray emission is due to Compton degradation of radioactive decay, particularly of ^{22}Na and ^{26}Al (Livio et al. 1992; Starrfield et al. 1992; Pistinner, Shaviv & Starrfield 1994). In the range 6–45 keV, Compton degradation might produce significant X-ray flux. Livio et al. (1992) argued that in this energy band X-ray emission is expected to be significant approximately 2 months after the outburst. However, the time for production of X-ray flux is inversely proportional to $v_{\rm ej}$ and was calculated only for $v_{\rm ej} \leq 1000$ km s^{-1}, lower than for V382 Vel. Therefore we do not rule out this mechanism being relevant at an earlier epoch. Gamma-ray observations of novae have not yielded very constraining upper limits so far (see Iyudin et al. 1995; Wanajo, Hashimoto & Nomoto 1999). The expected gamma-ray luminosity can be as high as 10^{35} erg s^{-1} and the derived X-ray luminosity is at least two orders of magnitude lower. At the average distance of a galactic nova it may still be detected with *BeppoSAX*. Regardless of $v_{\rm ej}$ and the related time-scale of emission, the X-ray flux would be higher in the PSD energy range than in the band covered by the MECS and LECS (see Livio et al. 1992).

In this paper we focus on the evolution of the hard X-ray emission (range 0.8–60 keV). No other classical nova has ever been observed immediately after maximum in such a broad energy range. We analyse the supersoft X-ray emission (below 0.8 keV) and the related white dwarf atmospheric model in a forthcoming paper (Orio et al., in preparation, hereafter Paper II).

2 OBSERVATIONS

V382 Vel was observed for the first time with *BeppoSAX* 15 d after the optical maximum, on 1999 June 7–8 for 42.5 ks with the two MECS, for 13.5 ks with the LECS, and for 23.3 ks with the PDS. The nova was then observed a second time on 1999 November 23 for 25.9 ks with the MECS, for 12.4 ks with the LECS, and for 12.4 ks with the PDS. Good data were selected from intervals when the elevation angle above the limb of the Earth was $> 4°$ and when the instrument configurations were nominal, using the SAXDAS 2.0.0 data analysis package. The standard PDS collimator dwell time of 96 s for each on- and off-source position was used together with a rocking angle of 210 arcmin. LECS and MECS data were extracted, centred on the position of V382 Vel using radii of 8 and 4 arcmin, respectively. The background subtraction for the imaging instruments was performed using standard files (1997 releases), but is not critical because the nova turned out to be a bright source. The background subtraction for the PDS was obtained during intervals when the collimator was offset from the source.

In 1999 June, the nova was detected with a count rate 0.1537 ± 0.0020 and 0.0620 ± 0.0026 count s^{-1} using the MECS and LECS, respectively (Orio, Torroni & Ricci 1999a). At higher energies, the 2σ upper limits obtained with the PDS were 0.0480 count s^{-1} in the 15–30 keV band and 0.0740 count s^{-1} in the 15–60 keV band. In the second *BeppoSAX* observation the count rate measured with the LECS was extremely high, 3.4860 ± 0.0021 count s^{-1}, due to the emergence of the central supersoft X-ray source (Orio, Parmar & Capalbi 1999b). In the range 0.8–10.0 keV the count rate was only 0.1030 ± 0.0038 count s^{-1}. As we mentioned in the introduction, in this paper we discuss the evolution of the hard X-ray emission, the only component detected by the MECS, with a count rate 0.0454 ± 0.0015 count s^{-1} (more than a factor 3 lower than in June). Even in 1999 November, there was no PDS detection with 2σ upper limit 0.0800 count s^{-1} in the 15–50 keV range.

For both observations we examined the possibility of variable X-ray flux. With Kolmorogov–Smirnov tests we found that the flux in the MECS is not variable by more than 15 per cent at the 80 per cent confidence level in the first observation, and by not more than 40 per cent in the second observation. These results are within the statistical fluctuations and do not imply significant variability.

3 SPECTRAL ANALYSIS AND INTERPRETATION

We translated the PDS measurements into upper limits to the flux assuming a power-law spectrum with a photon index of 2.1. (This result is not critically model dependent.) The 2σ upper limits obtained are: $F_{\rm x} < 6.7 \times 10^{-12}$ erg cm^{-2} s^{-1} at 15–60 keV in 1999 June, $F_{\rm x} < 4.2 \times 10^{-12}$ erg cm^{-2} s^{-1} in the 15–50 keV band in 1999 November. Ögelman, Krautter & Beuermann (1987) observed three novae using *EXOSAT* 3–7 months post-maximum: the upper limits for the flux obtained with the medium energy (ME) experiment at 6–50 keV were of the order of 10^{-11} erg cm^{-2}. Our *BeppoSAX* upper limits are lower than the flux measured in the MECS (regardless of the model assumed for the emission, see below), so we exclude radioactive decay as the main mechanism of emission, because we would measure a lower X-ray flux in the LECS–MECS range than at 16–45 keV with the PDS (see Section 1 and Livio et al. 1992). Lacking both a detailed spectral resolution and models of the evolving nebula predicting its X-ray luminosity, the observed X-ray flux of novae up to now has been fitted with thermal plasma models using a foreground absorbing column (Lloyd 1992; Balman et al. 1998). In Tables 1 and 2 we show the results of different spectral fits with models available in the XSPEC standard analysis package (Arnaud 1996). We fitted thermal models with and without ionization equilibrium, and a power-law model for comparison. We note that the latter describes the data less adequately, consistent with the belief that the X-ray emission is due to shocks. The thermal equilibrium model modified for low-energy absorption, MEKAL, is included to compare the data with Mukai & Ishida (2001) and with observations of V838 Her and V1974 Cyg. VMEKAL is used to test the effect of varying single element abundances. The non-equilibrium model NEI is included to test departures from ionization equilibrium. These may be expected when heating (arising from shocks) and subsequent cooling processes operate on a shorter time-scale than the ionization/recombination times of individual ions. At the energy range we are studying, hydrogen is fully ionized and in ionization equilibrium (see formula 1e of Rossi et al. 1997, for the recombination time), although the metals might be far from equilibrium. NEI is a constant temperature and single ionization parameter model; it is useful in characterizing the spectrum although it is not physically detailed. More detailed non-equilibrium models available in XSPEC are not specifically suited

Table 1. Spectral fit results to the *BeppoSAX* LECS and MECS spectrum of Nova Vel observed in 1999 June. The absorption, N(H), is in units of 10^{22} atom cm^{-2}. We report the best-fitting parameters and 2σ uncertainties for four different models. Z is the abundance compared to solar, ν is the photon index, F_x is the 0.8–10 keV absorption corrected source flux. *EM* is the best-fitting emission measure ($\int n_e n_H \, dV$; the tabulated values have been divided by 10^{56}).

Model	N(H)	kT (keV)	ν	Z	Fe	F_x (erg cm^{-2} s^{-1})	*EM* (cm^{-3})	χ^2/dof
MEKAL	16.8 ± 1.0	$6.1 \pm^{0.9}_{0.7}$		$0.09 \pm^{0.04}_{0.05}$		$(4.3 \pm^{0.3}_{0.4}) \times 10^{-11}$	24.3 ± 1.8	1.2
VMEKAL	16.8 ± 1.1	$5.4 \pm^{0.6}_{0.5}$		$4^{+0.5}_{-4.0}$	$0.21^{+0.12}_{-0.09}$	$(4.6 \pm 0.4) \times 10^{-11}$	9.9 ± 0.7	1.1
NEI	16.7 ± 1.0	$6.2 \pm^{1.0}_{0.7}$		0.09 ± 0.04		$(4.3 \pm 0.3) \times 10^{-11}$	26.8 ± 1.7	1.3
Power law	$19.3 \pm^{1.2}_{0.4}$		$2.4 \pm^{0.2}_{0.1}$			$(5.5 \pm^{1.7}_{1.1}) \times 10^{-11}$		1.6

Table 2. Same entries as in Table 1, for the best-fitting parameters to the *BeppoSAX* MECS and LECS (above 0.8 keV) spectrum observed for V382 Vel in 1999 November.

Model	N(H)	kT (eV)	ν	Z	Fe	F_x (erg cm^{-2} s^{-1})	*EM* (cm^{-3})	χ^2/dof
MEKAL	<0.18	616 ± 32		$0.06 \pm^{0.33}_{0.06}$		$(9.6 \pm 0.5) \times 10^{-12}$	11.3 ± 10.0	1.2
VMEKAL	<0.21	626^{+100}_{-60}		$0.04^{+0.10}_{-0.02}$	0.04 ± 0.20	$(9.6 \pm 0.5) \times 10^{-12}$	$10. \pm 2.0$	1.2
NEI	$0.04 \pm^{0.21}_{0.04}$	$775 \pm^{45}_{72}$		$0.08 \pm^{0.37}_{0.08}$		$(9.0^{1.0}_{2.5}) \times 10^{-13}$	9.9 ± 2.3	1.3
Power law	0.28 ± 0.12		5.6 ± 0.4			$(9.8 \pm 0.3) \times 10^{-13}$		1.2

to the physics of nova shells. We find that the thermal models yield remarkably similar results, so they are not well constrained by the data.

The first observation is adequately modelled by a thermal plasma at a temperature $kT \simeq 6$ keV. We compare this with $kT \simeq 10$ keV obtained by Mukai & Ishida (2001) at day 17 post-outburst. These authors found that the plasma temperature cooled again in four subsequent observations carried out using *RossiXTE*. The models in Table 1 also indicate unabsorbed luminosities of a few $\times 10^{34}$ erg s^{-1} (assuming a distance of 2 kpc) and $N(\mathrm{H}) = 0.6\text{–}2.7 \times 10^{23}$ cm^{-2} s^{-1}, which is unusually high. Mukai & Ishida (2001) derived a similar N(H) value at day 17 and later found that the intrinsic absorption decreased. In our bandpass the absorption is mainly due to photoelectric opacity of carbon and oxygen (Morrison & MacCammon 1983). In the direction of the nova the column density of neutral hydrogen is estimated to be 3.7×10^{21} cm^{-2} (Dickey & Lockman 1990). Platais et al. (2000) obtained a reddening consistent with $N(\mathrm{H}) \leq 2.5 \times 10^{21}$ cm^{-2}. The large value of N(H) at the early epoch is therefore due to *intrinsic* absorption of the ejecta, known to be rich in oxygen and probably carbon as well. The gas must have been optically thick to lower energy components in the nebular flux, such as the supersoft emission of the central source. Using the simple assumption that the emission measure $EM = \langle n_e^2 \rangle \, V_{\mathrm{shock}}$, where n_e is the electron density and V_{shock} is the volume filled by the shocked mass, the best-fitting *EM* in Table 1 is consistent with a shell filled in 15 d with a constant flow at $V_{\mathrm{ej}} = 4000$ km s^{-1} ($V_{\mathrm{shell}} \simeq 6 \times 10^{44}$ cm^3) and $n_e \simeq 2 \times 10^6$ cm^{-3} (a value which is on the upper range derived for nova shells). However, the shocks could also originate in dense clumps along the line of sight or from a zone which is deeply buried inside the nova shell, with higher density and much lower volume than the whole nebula. The two thermal models MEKAL and NEI seem to require low abundances for the best fit, however this does not imply low abundance Z for *all* elements: simply in order to match the data, it is necessary to decrease the strength of the Fe Kα line at 6.97 keV. It is understood using the VMEKAL model, the only one allowing specification of single element abundances. Varying other elements, we derive Fe = 0.0–0.39 within the 2σ confidence level, while enhanced abundances are instead perfectly acceptable for the other elements. The value of χ^2/dof decreases from 3.1 to 1.2, as we decrease Fe from 1 to the best-fitting value 0.21. In Fig. 1 we show (as an example, not implying it is necessarily the right model) the best VMEKAL fit (thermal plasma modified by low-energy absorption) to the combined LECS, MECS and PDS spectrum. We plot in the figure the data above 1.8 keV because there is no significant flux detection below. We compare the residuals of the fit with the reduced abundance and with solar iron. We remind the reader that the continuum optical depth at energy $kT = 6.97$ keV is negligible, $\tau_{\mathrm{cont}} = 0.084 N_{23}$ [where $N_{23} = N(\mathrm{H})/10^{23}$ cm^{-2}], and so is the line optical depth ($\tau_{\mathrm{line}} = 0.08 T_7^{-0.5} n_{e,5} L_{15}$, where T_7 is the temperature of the emitting region in units of 10^7 K, and L_{15} is the region thickness in units of 10^{15} cm).

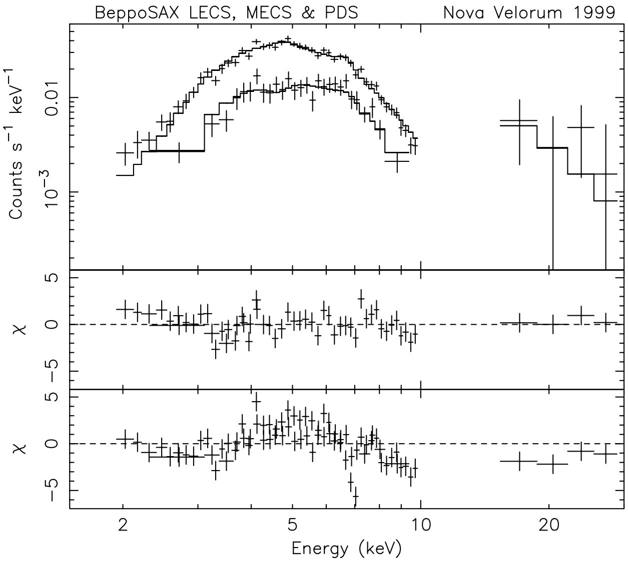

Figure 1. Observation of 1999 June: the LECS, MECS and PDS spectra and the best fit obtained with a VMEKAL model of a thermal plasma with depleted iron abundance (see text), enhanced abundance of all other elements (four times the solar value), $kT = 6.2$ keV, $N(\mathrm{H}) = 1.67 \times 10^{23}$ cm^{-2} (the reduced χ^2 is 1.13 per 83 dof). The residuals in units of σ are shown in the middle panel; below we plot the residuals of a fit done assuming solar abundances.

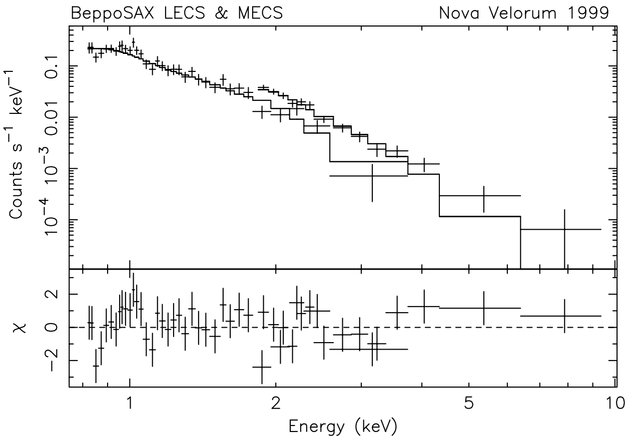

Figure 2. Observed LECS (only above 0.8 keV), and MECS spectrum of 1999 November and the best fit obtained with the VMEKAL model with $kT = 626$ eV, and $N(\mathrm{H}) < 2.1 \times 10^{21}$ cm^{-2} (see Table 2).

We simultaneously fitted the MECS spectrum and the LECS one, above 0.8 keV, observed in 1999 November with the same models. Above 0.8 keV, no X-ray emission is expected from the white dwarf atmosphere: preliminary fits to the whole 1–10 keV LECS spectrum indicate that we are also dealing with a separate spectral component. The plasma temperature is much lower, not exceeding 1 keV, and the value of N(H) is around the interstellar value, $\simeq 10^{21}$ cm^{-2}. We note that the large intrinsic absorption of the ejecta almost completely thinned out and the temperature range is comparable with the one derived for N Cyg 1992 six months after optical maximum (Balman et al. 1998). We still derive the best thermal fits with a low value of the total heavy element abundance. As the VMEKAL fit indicates, at low energy this is not due (or not only) to iron. It could be due to very unusual abundance ratios of different elements, or possibly it is an effect of the lack of ionization equilibrium that NEI is unable to model due to inadequate sophistication. However, ionization equilibrium is commonly assumed after several months from optical maximum (see Contini, Orio & Prialnik 1995, and references therein).

The LECS–MECS spectrum above 0.8 keV and the best fit with the VMEKAL model are shown in Fig. 2 for comparison with the first data set. We found a nebular component even in the range below 0.8 keV, where the flux from the central source was thought to be dominant. ‘Disentangling’ it from the atmospheric continuum is the subject of Paper II. The point we want to make here is that the shell had significantly cooled and that there was no X-ray emitting plasma at a temperature above 1 keV. Also, we notice that the total unabsorbed luminosity above 0.8 keV from the shocked shell at this stage had decreased to few $\times 10^{33}$ erg s^{-1} (approximately one order of magnitude).

4 CONCLUSIONS

A comparison with the observations published by Mukai & Ishida (1999, 2001) reveals that *RossiXTE* did not detect the nova on the third day after maximum in the 2.5–10 keV band (the upper limit to the flux was 2.5×10^{-12} erg cm^{-2} s^{-1}, see Mukai & Swank 1999). As we already mentioned, the nova was observed twice with *ASCA* shortly after the *BeppoSAX* observation in the 0.4–10 keV band. The flux was constant or had increased by not more than $\simeq 20$ per cent at day 17, and it remained at an approximately constant level until day 59 when it was observed for the last time with *RossiXTE* (Mukai & Ishida, 1999, 2001). Therefore the peak of the X-ray emission occurred during the third week after optical maximum, a few days after the first *BeppoSAX* observation, and a luminosity ‘plateau’ followed for at least 39 d. In the 0.8–2.4 keV range the unabsorbed X-ray flux was $\simeq 8 \times 10^{-12}$ and $\simeq 5 \times 10^{-13}$ erg cm^{-2} s^{-1} in the first and second *BeppoSAX* observation, respectively. These fluxes can be compared with the ones derived with *ROSAT*: for V1974 Cyg, the flux in the 1–2.4 keV range reached a few $\times 10^{-11}$ erg cm^{-2} s^{-1} at its peak around day 150 post-maximum (Balman et al. 1998) and for V351 Pup, $F_{\mathrm{x}} \geq 10^{-12}$ erg cm^{-2} s^{-1} in the 0.8–2.4 keV band 16 months post-maximum (see Orio et al. 1996). These two nova shells must have been intrinsically more luminous in these energy ranges and for a longer time, however no comparison is possible at an energy above 2.4 keV.

From our observations, and from the comparison with the *ASCA* and *RossiXTE* light curve derived between them by Mukai & Ishida (2001), we conclude the following.

(i) We attribute the hard X-ray emission to shocks in a small portion of the ejected nebula, in agreement with Mukai & Ishida (2001). Comptonized X-rays from radioactive decays are not definitely ruled out but are not the main source of the hard X-ray flux detected in these observations.

(ii) The unabsorbed X-ray luminosity in the range above 0.8 keV was a few $\times 10^{34}$ erg s^{-1} 15 d post-maximum. After a period of constant level, it decreased to a few $\times 10^{33}$ erg s^{-1} five and a half months later.

(iii) In the first observation, large intrinsic absorption of the ejecta prevented detection of the X-ray flux below 2 keV, while the ejecta were transparent to supersoft X-ray radiation in the second observation.

(iv) The observed X-ray emitting nebular plasma was at a temperature in the several keV range at 15 d, it reached 10 keV at day 17 and immediately started cooling. It cooled to a temperature below 1 keV at six months.

(v) There is a high probability that the shocked material was significantly depleted in iron and that the abundance ratios of different elements were peculiar, although we cannot be more specific. While Mukai & Ishida (2001) dismiss the derived iron abundance as due to non-availability of completely adequate models, we suggest that it might actually be real.

(vi) A comparison with *ROSAT* observations of V1974 Cyg and V838 Pup shows that the evolution and cooling of the hard X-ray component from nova nebulae occur on different time-scales.

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