Pair Annihilation and Radio Emission from Nova Muscae

D.C. Hannikainen\textsuperscript{1,2} & C.R. Kaiser\textsuperscript{2}
\textsuperscript{1} Observatory, PO Box 14, 00014 University of Helsinki, Finland.
\textsuperscript{2} Department of Physics and Astronomy, University of Southampton, Southampton, UK.

Abstract. In the hard X-ray spectra of some X-ray binaries line features around 500 keV are detected. We interpret these as arising from pair annihilation in relativistic outflows leading to a significant Doppler shift of the frequencies of the lines. We show that a small fraction of pairs escaping the annihilation region may give rise to the radio synchrotron emission observed in Nova Muscae 1991.

1. Introduction

The composition of the jets observed in Galactic X-ray transients, either electron-positron or electron-proton plasma, is still not fully established.

Here we review the arguments presented in \cite{1} where we proposed that the annihilation line features observed in the hard X-ray spectra of some X-ray transients arise from pairs in a bipolar outflow. At the time of annihilation, this outflow is already accelerated to relativistic bulk speeds causing a significant Doppler shift of the frequency of the annihilation lines. We also showed that the subsequent emission of radio synchrotron radiation from the outflow may be caused by only a small fraction of pairs escaping from the annihilation region. We apply this idea to radio and hard X-ray observations of Nova Muscae 1991. The energy requirements for this source rule out a large contribution of protons to the outflow.

2. Doppler-shifted annihilation lines

Conditions for a strong, narrow annihilation line. The direct annihilation of an electron-positron pair results in the production of two $\gamma$-ray photons, each with an energy of 511 keV in the rest-frame of the annihilating particles. In non-thermal plasmas relativistic electrons or pairs may be injected into the plasma. The injected pairs and those produced in the plasma may cool to sub-relativistic energies and thermalize before annihilating, thus leading to a narrow annihilation line \cite{2}. If the line is strong, it can rise above the Comptonization spectrum and becomes detectable. This requires a high pair yield, $Y$, defined as the ratio of the energy converted to pairs and the energy supplied to the plasma. The highest pair yields can be achieved when the plasma is ‘photon-starved’, i.e. when the number of injected relativistic photons strongly exceeds that of the injected soft photons \cite{3}. In this case, $Y \sim 0.25$ and a strong, narrow annihilation line above the Comptonization continuum becomes observable.

The observation of a narrow annihilation line most likely indicates a plasma with strong injection of non-thermal electrons or pairs. The injection of leptons into a spherical volume of radius $R$ is characterised by the compactness (e.g. \cite{2}).
\[ l_e = L_e \sigma_T / R m_e c^3, \]

where \( \sigma_T \) is the Thomson cross-section and \( L_e \) is the power of the electron injection, 
\[ L_e = (4\pi R^3 / 3) m_e c^2 \int Q_1(\gamma) (\gamma - 1) d\gamma. \]

Here, \( Q_1(\gamma) \) is the rate of injection of leptons with Lorentz factor \( \gamma \) per unit volume per unit time per unit \( \gamma \). If the compactness \( l_e \) can be inferred from the observations of an annihilation line, then the above equations can be used to constrain \( Q_1(\gamma) \).

**Relativistic Doppler-shifts.** Any emission of relativistically moving material is Doppler-shifted in its frequency. For material moving with bulk velocity \( v_b = \beta c \) at an angle \( \theta \) to the line of sight to the observer, the observed frequency, \( \nu \), of radiation emitted at frequency \( \nu' \) in the rest-frame of the material is given as

\[
\nu = \frac{\nu'}{\gamma_b (1 \pm \beta \cos \theta)} = \nu' \delta \pm, \quad (1)
\]

where \( \gamma_b \) is the Lorentz factor corresponding to the velocity \( \beta \) (e.g. [4]). The upper signs correspond to material receding along the line of sight to the observer while the lower signs indicate approaching material. From Equation (1) it is clear that radiation of material receding from an observer is always redshifted. However, for approaching material the emission may be blueshifted or redshifted, depending on the combination of \( \beta \) and \( \theta \). Solving Equation (1) for \( \beta \) we find that for \( \beta > 2 \cos \theta / (1 + \cos^2 \theta) \) the annihilation line arising from the approaching jet material will be redshifted. The range of velocities which result in such a Doppler redshift is largest for angles to the line of sight close to 90°.

### 3. The case of Nova Muscae

Nova Muscae (GRS 1124–684) was discovered on 1991 Jan 8 by Granat ([5], [6]) and Ginga [7]. During monitoring observations, a strong, narrow line near 500 keV was detected on Jan 20–21 which had not been noted before. The line flux was observed to increase during the observation within the space of a few hours. Unfortunately, the observations stopped before the line flux decreased again, implying a lifetime of the line emission of at least 10 hours. Simultaneously to the strong line near 500 keV, there was also increased emission detected near 200 keV. The spectrum obtained with Granat during 1991 Jan 20–21 is shown in Figure 1.

The original discovery also triggered a radio monitoring programme using the Molongolo Observatory Synthesis Telescope (MOST) at 843 MHz ([8], [9]). [9] note four distinct features in the lightcurve. There is a general decay of the radio flux from the very beginning of the programme continuing until about January 22. There is another flare observed from January 31 until around February 5. Finally, a short flare lasting only one day was observed by MOST at 843 MHz on January 24 with a measured flux density of 24 mJy. In the following we will concentrate on the detection of the \( \gamma \)-ray lines on January 21 and the brief radio flare on January 24. We speculate that the same ejection event is responsible for the emission at opposite ends of the electromagnetic spectrum observed on the two days.

**Constraints from the annihilation line.** We assume here that the two \( \gamma \)-ray lines observed in the spectrum of Nova Muscae arise from pair annihilation in a relativistic bipolar outflow from the very centre of the system. In this model, the line at 474 keV is associated with the approaching component while that at 194 keV arises from the receding component. We find \( \theta = 60° \pm 7° \) for the angle to the
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The best-fitting model to the spectrum of Jan 21. The large figure shows the full spectrum from the last third of the Jan 20–21 observation, showing the emergence of the annihilation features. The inset shows the data points around 474 keV used in the fitting, while the bottom panel shows the residuals of the model to the data in normalized counts/second.

Figure 1 shows our best fit with a reduced \( \chi^2 \)-value of 1.35 (for 84 d.o.f). The free parameters, \( l_e \sim 3000 \) and \( l_s \sim 50 \), imply a strongly photon-starved plasma. However, the values of the model parameters are not well-constrained and reasonable fits to the data can be obtained for \( l_e > 100 \). Re-arranging the equation above yields \( L_e = R m_e c^3 l_e / \sigma_T \). Substituting in our lower limits for \( R \) and \( l_e \), we find \( L_e \geq 7 \times 10^{30} \) W. It follows that \( Q_0 = 9 \times 10^{26} \) m\(^{-3} \) s\(^{-1} \) for this lower limit. The
rate at which relativistic electrons are injected is then $\dot{N}_{\text{inj}} = 3 \times 10^{43}$ particles s$^{-1}$. This is comparable to the observed annihilation rate of $2 \times 10^{43}$ particles s$^{-1}$.

**Implications of a bipolar flow.** In the case of an ejection event shorter than 10 hours, the annihilation rate would decrease dramatically as the ejected material travels outwards and expands. In the model presented here we argue that the bulk of the outflow containing the pairs is already accelerated when they annihilate, thus explaining the redshifts of the two observed lines. The velocity of the outflow is then 0.84$c$.

The energy required to drive the outflows is enormous. As the relativistic electrons necessary for pair production are highly relativistic, their mass in the rest frame of the outflow material is given by $\gamma m_e$. Therefore, the total kinetic power of the relativistic electrons, as measured in the source rest frame, injected into the outflow can be approximated as $E_{\text{kin}} = V Q m_e c^2 (\gamma_b - 1) \int \gamma^{1-p} d\gamma \sim 6 \times 10^{31}$ W. In this estimate we have used the limiting values for the electron compactness, $l_e = 100$, and the size of the emission region, $R = 2 \times 10^5$ m. Any increase in these parameters will also cause the energy estimate to rise. Therefore, the lower limit on $E_{\text{kin}}$ corresponds already to about 80% of the Eddington luminosity of a $6 M_\odot$ black hole. Balance of electrical charge requires the presence of positively charged particles in the outflow. If these are protons with negligible thermal energy but travelling at the necessary bulk velocity, then another $4 \times 10^{33}$ W in kinetic energy are required. This is at least a factor 50 more than the Eddington luminosity. This energy injection into the outflow has to be sustained for more than 10 hours and thus makes a large proton content in the jet very unlikely.

The only alternative is then that from the very beginning of the ejection the outflow material in the annihilation region consists of virtually a pure pair plasma. This removes the requirement of relatively inefficient pair production from relativistic electrons. The pairs must be injected into the relativistic bulk flow with a relativistic velocity distribution to explain the strength of the annihilation line [12], the cooling within the outflow and then annihilation at a rate of $2 \times 10^{43}$ s$^{-1}$. In this case, the required kinetic power is about $6 \times 10^{30}$ W, or 8% of the Eddington luminosity.

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