The Differential Emission Measure Distribution of EQ Pegasi Observed by BeppoSAX

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Abstract. Broad band BeppoSAX observations of EQ Pegasii are analyzed using the CHIANTI database and a differential emission measure (DEM) versus temperature distribution of coronal plasma. Comparison is shown with the two temperatures modelling usually performed in the data reduction of broad band observations of active stars. The main peaks of the DEM distribution agree with the two-temperatures solution with similar reduced $\chi^2$ values. The chemical composition necessary to get the best fit shows high FIP elements less abundant than their photospheric values and low FIP ones as abundant as photospheric ones. A flare is detected during the first part of the observation: the flaring region covers only a very small fraction of the stellar surface.

1. The star

EQ Peg is one of the brightest and most active late-type stars, and consists of a dM5e+dM4e visual binary system. EQ Peg AB has been extensively investigated over large part of the electromagnetic spectrum and multifrequency observations have been performed.

One of the authors have observed EQ Pegasi system using the Extreme Ultraviolet Explorer Satellite (EUVE) on August 29 and 30, 1993 (Monsignori Fossi et al. 1995): flare activity occurred during the observation and strong highly ionized iron lines were detected (Fe XVIII to Fe XXII), showing that high temperature ($10^7$ K) plasma was present.

The main characteristics of this system are summarized in Table 1.
Table 1. Main characteristics of the EQ Pegasi (GL 896 AB; BD +19°5116) binary system

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>6.5 pc, 0.155&quot; parallax</td>
<td>Gliese 1969</td>
</tr>
<tr>
<td>Separation</td>
<td>3.7 arcsec</td>
<td>Kukarkin 1969</td>
</tr>
<tr>
<td>Period</td>
<td>∼180 years</td>
<td>Kukarkin 1969</td>
</tr>
<tr>
<td>Spectral type</td>
<td>dM4e and dM5e</td>
<td>Joy and Abt 1984</td>
</tr>
<tr>
<td>V magnitude</td>
<td>10.38 and 12.4</td>
<td>Pettersen et al. 1984</td>
</tr>
<tr>
<td>Radii</td>
<td>∼0.23 $R_{Sun}(A)$ 0.38 $R_{Sun}(B)$</td>
<td>Bastian 1990</td>
</tr>
<tr>
<td>Rotation</td>
<td>2.7 days for GL 896A</td>
<td>Doyle 1987</td>
</tr>
</tbody>
</table>

2. BeppoSAX Observation

The active binary star EQ Pegasi has been observed with the LECS and MECS instruments on board BeppoSAX from December 3, 1997, 10:12 to December 4, 1997, 05:12. The rise and the decay of a flare occurred during the first part of the observation; it has been clearly detected in all the energy bands from 0.1 to 5 keV (Figure 1).

The data were observed in 82 energy channels of LECS, from 0.17 to 2.8 keV, and in 45 energy channels of MECS, from 1.6 to 9.7 keV, as counts/keV/s. The two stars were not resolved in the present observation.

2.1. The two-temperature modeling

The total count-rates were fitted with a two-temperature, optically thin plasma model using the XSPEC 11 code. Emissivities came from APEC, a code based on the ATOMDB database (Smith et al., 2001).

The hydrogen column density along the direction the star was measured by EUVE to be $N(HI) = 1.34 \times 10^{18}$ cm$^{-2}$, and it does not appreciably affect the photon energy range observed by the BeppoSAX detectors.

The model parameters fitted to the observations are

**Temperature of 1$^{st}$ component** = $1.48^{+0.31}_{-0.25}$ keV ($7.14 \leq \log T \leq 7.29$)

**Temperature of 2$^{nd}$ component** = $0.62^{+0.08}_{-0.06}$ keV ($6.72 \leq \log T \leq 6.90$)

**Metallicity of 1$^{st}$ component** = $0.6^{+2.0}_{-0.4}$

**Metallicity of 2$^{nd}$ component** = $0.4^{+2.8}_{-0.2}$

The uncertainties in the metallicities are very large, moreover no conclusions can be made regarding any possible FIP effect in the abundances of the system.

3. The DEM model

An isothermal modeling of the corona of active stars is a rather crude approximation; this approach is not correct for the outer solar atmosphere and has been questioned by high spectral resolution data of active stars. In the present work we replace this approach by using a continuous temperature model: the
Figure 1. Photometric light curve of EQ Pegasi using LECS and MECS integrated bands. A rise and fall event lasting about 30000 secs occurs in the first part of the observation. As usual in solar flares the hard x-ray component develops well in advance than the softer component.

Differential Emission Measure distribution (DEM), using diagnostic techniques commonly employed to study the solar corona since almost 30 years.

The DEM analysis was carried out using the CHIANTI database (Dere et al. 1997, Young et al. 2003) to evaluate the theoretical spectral distribution of the plasma emissivity $\varepsilon(T, \lambda)$. Introducing the standard DEM definition $\text{DEM}(T) = n_e^2 \frac{dv}{dT}$, the flux $F_{\text{channel}}$ measured at Earth (counts cm$^{-2}$ s$^{-1}$) in each channel can be written as

$$F_{\text{channel}} = \frac{1}{4\pi d^2} \int_T \varepsilon_{\text{channel}}(T) \text{DEM}(T) dT \tag{1}$$

The DEM distribution that minimizes the $\chi^2$ between measured flux and predictions from Equation 1 has been evaluated and it is shown in Figure 2. Only few temperature bins are constrained by the observations.

The DEM approach allows a more precise determination of element abundances, by calculating the corrections to an assumed set of values. In the present work, we assumed the solar coronal abundances from Feldman (1992).

In order to get the best fit it was necessary to change the assumed chemical composition of a few elements. No evidence exists that photospheric abundances of EQ Peg are different from the solar ones. The ratio of the adopted coronal abundances over the photospheric ones is shown in Figure 3 (right), suggesting the presence of a FIP effect.
Figure 2. The DEM distribution versus temperature for the total observation. Only a few temperature components are properly constrained, at logT=6.8, 7.0 and 7.2 (T in K). Only upper limits can be defined for the other temperature bins. Diamonds show the results based on EUVE observations in Monsignori Fossi et al. (1995).

Figure 3. **Left**: The best fit computed total count rate per keV (thick line) is compared with measured ones for each LECS and MECS channel; the region from 2 keV to 2.5 keV is common to both instruments. **Right**: ratio of the best fit coronal EQ Peg abundances to the solar photospheric ones; results suggests the presence of a FIP effect.

4. The flare event

The count rates of the channels have been integrated over time steps of 5000 sec, and grouped according the same effective temperature \( T_{\text{eff}} \), defined as

\[
\log T_{\text{eff}} = \frac{\int G_j(\log T)\varphi(\log T) T d\log T}{\int G_j(\log T)\varphi(\log T) d\log T}
\]

This procedure allows us to monitor the response to the flare of the plasma at any temperature. The integrated DEM over the temperature interval of the flare
is about $1.5 \times 10^{51} \text{ cm}^{-3}$, that for any density larger than $n_e = 10^{11} \text{ cm}^{-3}$ implies a linear dimension of the source of about $5 \times 10^9 \text{ cm}$, and a covered area about $6 \times 10^{-3}$ that of the stellar surface, so that the flare interests a small fraction of the star.

5. Conclusions

A BeppoSAX observation of EQ Pegasi, performed in December 1997, has been analysed both using the APEC theoretical spectrum and a 2-temperature model for the corona, and using the CHIANTI database and a continuous temperature distribution (DEM). Both procedures fit the data with similar reduced $\chi^2$ values, and the two resulting temperatures agree fairly well with the peaks of the DEM distribution.

With the DEM, we obtained some insight on corrections to the chemical abundances of a few elements (Fe, Si, Mg, S, O); the measured abundances suggest that the EQ Peg coronal plasma is affected by the FIP effect, showing that the high FIP elements in corona are less abundant than in photosphere.

A flare is well detected in the higher energy channels ($\geq 0.82 \text{ keV}$) whose signal is mainly due to the temperature regimes $\geq 6 \times 10^6 \text{ K}$. We estimate that it concerns less than one hundredth of the stellar surface.

The coldest component is at about $4 \times 10^6 \text{ K}$ with a volume emission measure $4 \times 10^{50} \text{ cm}^{-3}$; taking into account the surface of the two stars this corresponds to a mean linear emission measure $\int h N_e^2 dh = 4 \times 10^{28} \text{ cm}^{-5}$, one order of magnitude larger than the quiet sun.

References

Young, P.R., et al. 2003, ApJS, 144, 135