

# Spectral line enhancements as signatures for stellar activity: AD Leonis – an example

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**Abstract:** A high level of stellar activity in the form of frequent flaring and frequent mass ejections can lead to the total loss of exoplanetary atmospheres due to evaporation and erosion. Simulations have shown such scenarii for close-in exoplanets orbiting M-stars. Information on stellar flaring activity is accessible more easily than information on stellar mass ejections, simply due to the difference in detection. In the National Aeronautics and Space Administration/Far Ultraviolet Spectroscopic Explorer spectra of the dM star AD Leonis we find an interesting event lasting for only one spectrum. The first component of the OVI (103.19 nm, 103.76 nm) duplet shows an enhancement of the blue wing, shifted by about 90 km s<sup>-1</sup>. This event occurred one spectrum after a flare. We discuss several solar/stellar phenomena that might produce such a spectral feature and could therefore explain this event.

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## Introduction

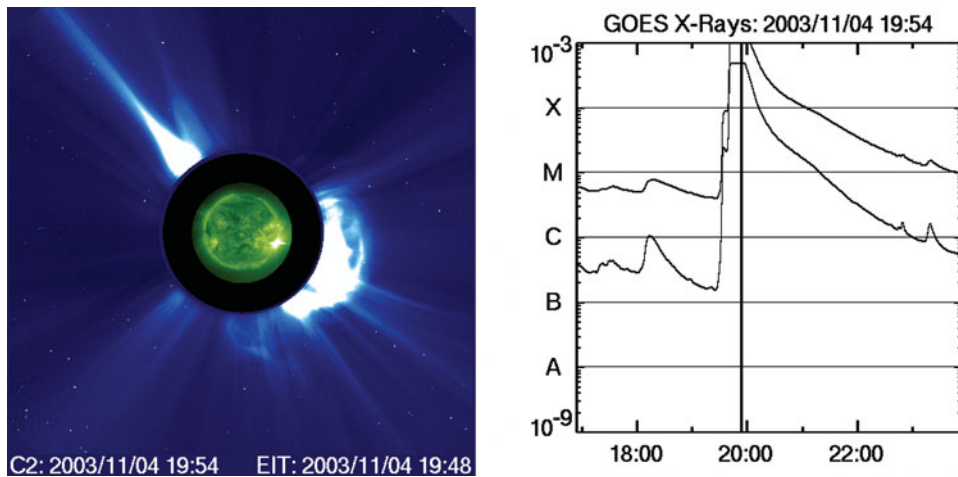
Solar sporadic outbreaks of radiation (flares) have been known since the middle of the 19th century (Carrington 1859). Solar sporadic outbreaks of highly energetic particles (CMEs) have been known since the 1970s (Tousey 1973, Gosling *et al.* 1974). Powerful solar flare and CME events are correlated on a temporal and spatial scale (see Fig. 1); weaker events often show no correlation.

Stellar flares have been known since the 1940s on ultraviolet (UV) Ceti type stars. In the middle of the 1970s, flares were also detected in X-rays and today we know, due to sensitive instruments, that every star which has a corona is also variable in X-rays. This stellar phenomenon can be easily detected in lightcurves.

Stellar CMEs are indirect and therefore more difficultly to detect. Indications of stellar mass ejections were detected several times on young and active dM stars as line asymmetries in Balmer lines. Houdebine *et al.* (1990) analysed a set of optical spectra of the young (0.2 Gyr) and active M 3.5 Ve star AD Leonis. The authors detected a distinct blue wing enhancement of the H-gamma (434.1 nm) Balmer line, decreasing with time until it vanished completely. They deduced a Doppler velocity of 5800 km s<sup>-1</sup>, which is about

twice the value of the fastest solar CMEs obtained by the 3.6 m telescope at the European Southern Observatory (ESO). Further, UV dimmings known from the sun to be correlated with CMEs were detected on the active M dwarf EV Lacertae during several hours of International Ultraviolet Explorer (IUE) observations (Ambruster *et al.* 1986). A drop in the UV flux lasting for 1.5 hours of the star was interpreted as a mass ejection event. Extreme Ultraviolet Explorer (EUVE) observations of the young dM star AU Microscopii revealed a powerful flare with a decay time of a day. Cully *et al.* (1994) reconstructed the strongest spectral lines successfully by including the assumption of an ejected magnetically confined plasma in their model. The deduced mass and kinetic energy of this event was a factor 10 000 higher than the strongest solar CME events. Fuhrmeister & Schmitt (2004) detected a huge flare on the old dM9 star DENIS104814.7-395606.1. They further found a blue wing asymmetry in the Balmer H-alpha and H-beta lines, which they favour to be a signature of plasma that has been ejected into the observer's direction.

The relevance for such investigations is not only the interest in applications for stellar mass and/or momentum loss, but also for non-thermal planetary mass loss. It has been shown (Grießmeier *et al.* 2005; Khodachenko *et al.* 2007;



**Fig. 1.** Shown is a solar example of the correlation of mass ejections and flares. During the last solar maximum a set of powerful flare/CME events occurred, one of which is shown. The left panel shows a Large Angle and Spectrometric COronagraph (LASCO) image of the 4 November 2003 Halo CME. Overlaid is an Extreme UV Imaging Telescope (EIT) image showing the corresponding X-class flare occurring on the eastern solar limb. The right panel shows a GOES X-ray lightcurve showing the rapid increase of solar X-ray flux.

Lammer *et al.* 2007) that the combination of a close orbit, frequent CME impacts and a weak planetary magnetic field, acting as a protector against high energy particles, can lead to the total erosion of a planetary atmosphere. On active and young stars, the radiation environment is certainly higher than on older stars. Higher temperatures lead to the expansion of upper planetary atmospheric layers, on the other hand a fast and dense stellar wind pushes the Magnetopause closer to the planet, resulting in a volume of expanded atmosphere, which is then unprotected against high energetic particles, and can then be easily eroded. Information on the frequency, mass, velocity, and the kinetic energy of stellar mass ejections is crucial for models that simulate the influence of high-energy particles on planetary atmospheres. Since the parameters (velocity, energy, mass) of stellar mass ejections of active stars are expected to be larger (c.f. Houdebine *et al.* 1990) than solar values, the influence on atmospheres of orbiting planets will be more efficient.

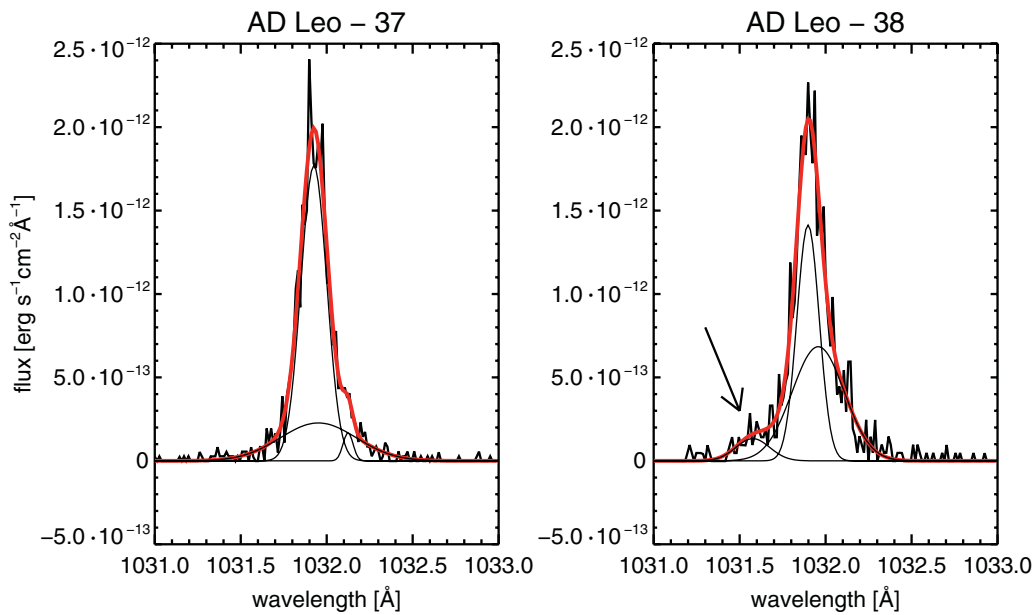
### Observations

We use data from the National Aeronautics and Space Administration (NASA)/Far Ultraviolet Spectroscopic Explorer (FUSE) satellite, which monitored the active and young dM star AD Leonis for more than 18 hours, resulting in 41 spectra and lightcurves. The FUSE covers the FUV wavelength region from 90.5 to 118.7 nm, including strong stellar transition region lines (CIII (99.7 nm) singlet, CIII (117.6 nm) multiplet, and OVI (103.2 nm, 103.8 nm) duplet). The observations were performed using the LWRS aperture. The raw data files were calibrated with FUSE's calibration pipeline CalFuse v3.2. A re-calibration of the data allows data screening, accessible only in the Intermediate Data Files (IDFs), which are generated through the calibration process from which the calibrated spectra emerge. The data

are corrected for Inter Stellar Material (ISM) absorption affecting the mainly the CIII (99.7 nm) singlet (cf. Guinan *et al.* 2003) and the spectra are re-wavelength calibrated using ISM absorption lines (CIII) and Hubble Space Telescope (HST) spectra overlapping in the long wavelength region of the FUSE. The data are screened for night-time events only and the lightcurves are extracted using wavelength windows centred on the above-mentioned strong transition region lines to avoid geocoronal emission.

### Results

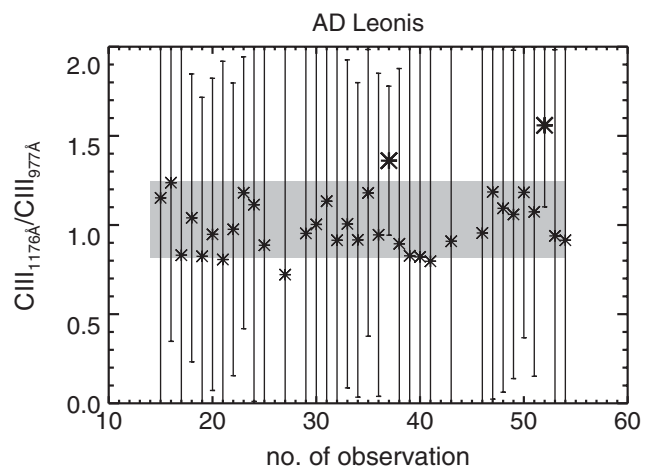
AD Leonis showed, during 18 hours of observations, two distinct flares in the lightcurves (see Christian *et al.* 2006, who analysed the data in view of opacity effects) with energies of 0.16 and  $0.25 \times 10^{32}$  erg. The flares appear distinct in the CIII (117.6 nm) multiplet, but less distinct in the OVI (103.2 nm) duplet and CIII (97.7 nm) singlet. The analysis of the full width at half maximum (FWHM) of the whole spectral time series of the OVI duplet showed a maximum at spectrum no. 38, which is one spectrum after the flare in spectrum no. 37. Both spectra are characterized by broad asymmetric wings. Flare spectrum no. 37 shows a red wing asymmetry, and spectrum no. 38 shows a broader blue wing asymmetry (indicated by an arrow in Fig. 2) shifted by about  $90 \text{ km s}^{-1}$  from the line centre of the OVI. The FUSE offers, due to its wavelength coverage, the possibility of investigating the electron density sensitive line ratio CIII (117.6 nm)/CIII (97.7 nm). This ratio was found to be increased in solar active regions (Dupree *et al.* 1976). During the flares of AD Leonis, the ratio was also increased (see Fig. 3). CMEs cause regions of increased electron density (c.f. Kathiravan & Ramesh 2005), which is assumed to reflect in the density sensitive line ratio. However, a correlation of CMEs and the increase of the carbon ion line ratio has not been proven so far.



**Fig. 2.** Plotted is spectrum no. 37 and no. 38 of the FUSE/AD Leonis time series. One can clearly see the blue wing (indicated by an arrow) enhancement in the OVI (103.2 nm) transition region line in the right panel. The deduced Doppler velocity is  $90 \text{ km s}^{-1}$ . The line profile could be fitted with a multi Gaussian function, reproducing the enhancement.

## Discussion

Since mass ejections on stars are only indirectly detectable, and accessible only via signatures, which are mostly known from the sun, possible phenomena that could cause those signatures have to be discussed. The deduced velocity of the spectral event shown in Fig. 3 is about  $90 \text{ km s}^{-1}$ , not high compared to average solar CMEs, which makes it more difficult to interpret the spectral feature correctly, since quiescent solar plasma motions were detected in the range of  $5\text{--}100 \text{ km s}^{-1}$ . Even solar chromospheric evaporation was found to be in the range of  $100 \text{ km s}^{-1}$  (Teriaca *et al.* 1999). The spectral feature occurred one spectrum after a flare spectrum corresponding to a difference in time of about two hours. Although lightcurve no. 38 shows no variation, the mean countrate is clearly above the quiescent value, therefore the phenomenon producing the spectral feature (see Fig. 2) could be related to the flare in lightcurve no. 37, but this remains unclear, due to the large difference in time. Another possible explanation for the spectral feature is a plasma cloud co-rotating with the star (see Fuhrmeister & Schmitt 2004). If this is the case, then the height of the cloud must not exceed the Keplerian co-rotation radius. With the deduced velocity of the spectral feature and the rotation period of AD Leonis, we can measure the height of the cloud. The comparison of the cloud height and the Keplerian co-rotation radius shows that the deduced velocity is too large for a stable plasma cloud. The velocity that one deduces is a projected velocity, since we do not know the angle of propagation. Therefore, in addition, small velocities can be attributed to mass ejection events. Let us assume a plasma (CME) propagation with a pitch angle of  $269^\circ$  (a pitch angle of  $270^\circ$  corresponds to an



**Fig. 3.** Shown is the variation of the carbon ion line ratio in time for the AD Leonis NASA/FUSE data. The flares in the data (no. 37 and no. 52) are marked by big asterisks. The shaded area represents the mean line ratio of the whole data set together with the measurement uncertainty. As one can see, both flares show the highest values (c.f. Christian *et al.* 2006).

orthogonal propagation from the eastern stellar limb) and a normal velocity component of  $90 \text{ km s}^{-1}$ , then the resulting or real velocity corresponds to  $5156 \text{ km s}^{-1}$ . This estimation gives an upper limit to the real velocity of the possible mass ejection event.

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