EURD: THE MISSION AND THE STELLAR ABSOLUTE FLUXES OF B-TYPE STARS *

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Abstract. We present here stellar spectra of B stars obtained with the EURD spectrograph, one of the three instruments on board MINISAT-01. EURD is a spectrograph specially designed to detect diffuse radiation in the wavelength range between 350 and 1100 Å with 5 Å spectral resolution. EURD main scientific targets are: the spectrum of interstellar medium, atmospheric airglow, decaying neutrinos, Moon and early type stars.

1. Introduction

Stellar observations in the FUV have been until now controversial due to the difficulty in obtaining an absolute calibration. The different observations performed to date have lacked of absolute calibration or given different flux levels for the same target with different instruments. The Copernicus satellite (Rogerson *et al.*, 1973), with a very good spectral resolution of 0.05 Å and several years of observations, could not give absolute fluxes due to sensitivity variations in the detector throughout the mission life. The calibration of the UV-spectrograph onboard Voyager spacecraft (Broadfoot *et al.*, 1977) has been a subject of discussion. Several rocket flights performed between 1979 and 1989 (Brune *et al.*, 1979; Carruthers *et al.*, 1981; Woods *et al.*, 1985; Cook *et al.*, 1989) have given very low fluxes compared with model atmospheres and with Voyager fluxes. More recently ORFEUS (Hurwitz *et al.*, 1991), HUT (Davidsen, 1990) and UVSTAR (Stalio *et al.*, 1993) spectrographs have flown onboard the Space Shuttle and used white dwarf observations as inflight calibration. In Table I are shown the most representative FUV stellar observations carried out up to now. Until FUSE satellite starts giving

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TABLE I
Satellite stellar observations in the FUV

Mission	Wavelength	Resolution	Date
COPERNICUS	950–1350 Å	0.05 and 0.2 Å	1973
VOYAGER 1,2	525–1200 Å	18 Å	1977
ORFEUS-SPAS	900–1170 Å	0.35 Å	1991
HUT	910–1840 Å	2–3 Å	1990
UVSTAR	500–1250 Å	1, 4.5 and 12 Å	1993
EURD	350–1100 Å	5 Å	1997

results, EURD stellar observations can give us important information on the stellar distribution of energy of OB stars.

EURD (Espectrógrafo Ultravioleta extremo para la Radiación Difusa) is an imaging spectrograph flying onboard the spanish satellite MINISAT-01 which has succesfully reached two years of observations and is funded to fly for at least one more year. A detailed description of the instrument can be found in Bowyer *et al.* (1997). In Table II we show the main characteristics of the instrument, which has a sensitivity 100 times better than previous observations in the extreme and far ultraviolet. In this workshop there is a description of the results obtained on the main scientific objectives of the EURD mission: airglow observations (López Moreno *et al.*, 2001), decaying neutrino line (Bowyer *et al.*, 2001), interstellar medium emission (Edelstein *et al.*, 2001) and this paper about stellar observations. A contribution specially dedicated to the explanation of the process of EURD spectrograph data reduction (Gómez *et al.*, 2001) can be found also in this volume.

2. Observations

EURD is a spectrograph specially designed to detect diffuse radiation in the wavelength range between 350 and 1100 Å with 5 Å spectral resolution. Bright and nearby OB stars emit enough photons to be detected by EURD above 912 Å. Since EURD always observes in the antisun direction, stars within $\sim 13°$ from the ecliptic are detected and their spectra extracted following the steps described in this volume by Gómez *et al.* (2001). EURD observations take place during the orbital eclipse to avoid the intense geocoronal emission of the upper atmosphere.

The large dimensions of EURD field of view ($25.6° \times 8.4°$) give the possibility of detecting the same star for several consecutive days, up to 25 days, depending on the coordinates of the star and the position of the slit (For instance, α Virginis was observed during 8 days in 1998 and 25 days in 1999). This long observation

TABLE II
EURD main characteristics

Bandpass	350–1100 Å
Short wavelength spectrograph	350–800 Å
Long wavelength spectrograph	500–1100 Å
Spectral resolution	5 Å
Spatial resolution	better than 0.1°
Field of view	25.6° × 8.4°
Grating	8 cm diameter
	18 cm focal length
	holographically ruled 2460 lines mm^{-1}
Grating overcoating	LWS: Silicon carbide
	SWS: Boron carbide
Detector	Low-noise microchannel plate with anticoincidence guard
Detector photocatode	LWS: Chemical treatement
	SWS: Magnesium fluoride
Size (each spectrograph)	40 × 40 × 13 cm
Weight (each spectrograph)	11 kg

of α Vir provided us with a signal to noise ratio of the order of 3000 with a total integration time of 1.06×10^5 s.

As it is explained in Gómez *et al.* (2001), the EURD field of view is transformed into a spectral image that retains spacial information in the Y axis and gives spectral dispersion in the X axis (MINISAT X and Y inertial axes). Then, depending on MINISAT attitude, only stars in our field of view with different Y coordinates can be separated into individual spectra. Stars with approximately the same X coordinate would produce spectral emission at the same location and therefore their emissions would be completely blended. MINISAT can spin around the Z axis, which gives us the possibility of, in some cases, solve the problem by orienting the slit of the spectrograph with such an inclination that the stars do not have the same X coordinate on the field of view.

An example can be seen in Figure 1 in which three stars of approximately the same galactic latitude but different galactic longitude are seen superposed on the EURD image of 1998. Rotating the slit, so as to have galactic longitude along the Y axis, would produce the individual spectrum of these three stars with more than 6° separation, enough to be seen as individual spectra by EURD, but the central star on the slit will be blended with the contiguous one (here almost out of the spectral image, leftmost trace).

More complicated or even impossible to solve is the case of nearby star clusters of OB stars like the Pleyades or crowded stellar fields in which the stars are so close

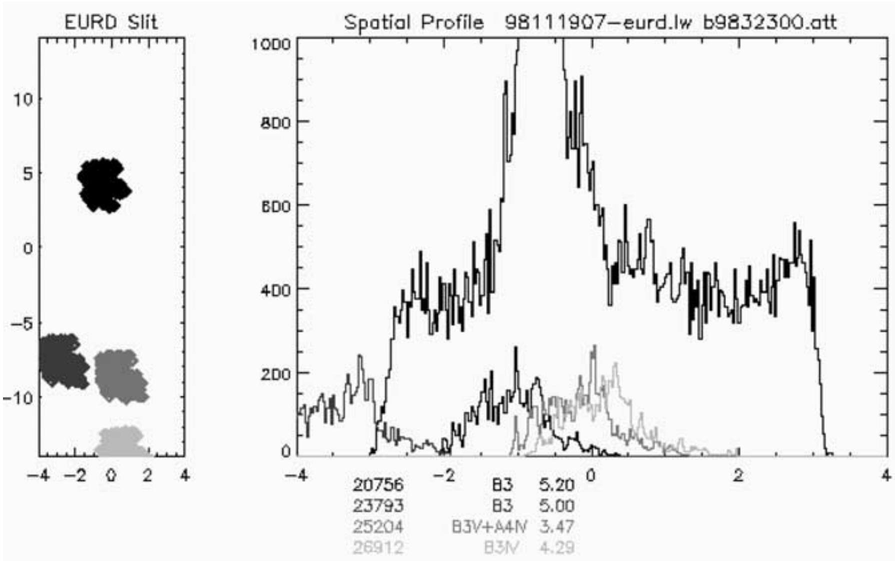

Figure 1. Left: position of the stars in EURD field of view. Right: (upper line) observed flux and (lower lines) expected trace of every star on the detector (time spent in each position of the detector from –4° to +4° in the Y coordinate). The identified stars are shown at the bottom.

TABLE III
EURD stellar observations

Star	Spectral type	V mag.
HD 19374	B1.5 V	6.10
HD 87901	B7 V	1.33
HD 91316	B1 Ib SB	3.856
HD 116658	B1 V	0.98
HD 138485	B3 V	5.50
HD 157056	B2 IV	3.26
HD 175156	B3 II	5.10
HD 175191	B2.5 V	2.078
HD 205637	B3 V:p	4.70
HD 212571	B1 Ve	4.64

together in the field of view that in our spectral image the stellar emission falls on the same or on contiguous pixels and it is impossible to extract the individual spectra of the stars.

At this moment we have reduced only the cases where only one star appears in the field of view. They are listed in Table III with their main parameters.

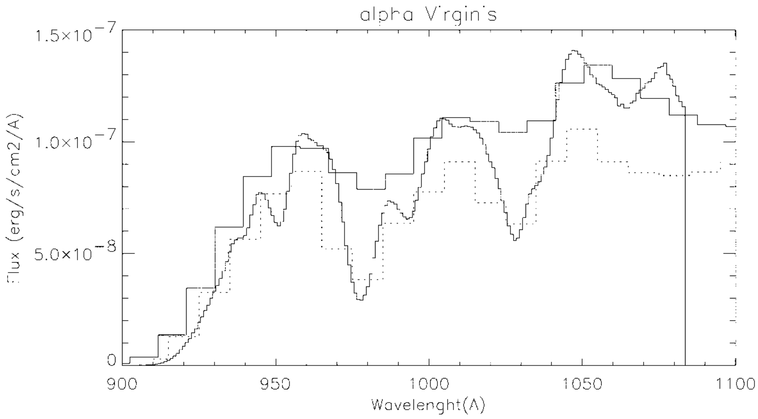

Figure 2. Spectrum of α Vir as observed by EURD and Voyager superposed on the Kurucz model computed for α Vir binary system and normalized to the IUE spectrum (dotted line).

3. Absolute Fluxes

After identifying and extracting the spectrum in raw counts and correcting for the instrumental background and the atmospheric emission, the counts are transformed to ergs^{-1} cm^{-2} s^{-1} Å^{-1} using an inflight calibration performed by means of simultaneous observation of the full Moon with EURD and the EUVE satellite. Since the largest wavelength detectable by EUVE is 760 Å, the calibration had to be extrapolated larger than that to cover the whole EURD range. We checked this extrapolation with α Virginis, the brightest star we have observed, comparing the resultant absolute flux with model atmospheres and with previous observations. In Figure 2 we can see the EURD spectrum of α Virginis compared with Voyager observation and with the Kurucz model fitted to the IUE range for zero reddening (Morales *et al.*, 2000).

The similarity of the fluxes obtained by Voyager and EURD is remarkable, with only some differences in the lines of the Lyman series of hydrogen that we attribute to atmospheric absorption in our data. The flux of the Kurucz model is slightly lower than EURD fluxes, consistent with ORFEUS and HUT observations.

The fluxes obtained by EURD with the inflight Moon calibration agree with Voyager fluxes obtained by Holberg *et al.* (1982) by fitting their data with a white dwarf model atmosphere. The independence of the absolute calibration method used by the two works supports the reliability of our flux calibration.

4. Intrinsic Spectral Energy Distribution

The only star in Table III with negligible reddening is α Vir (HD 116658). The rest need a reddening correction in order to be compared to Kurucz model atmospheres.

A very small $(B - V)$ color excess in the visible produces a strong absorption at EURD wavelengths ($\lambda < 1100$ Å). In fact the stars we have been able to detect with EURD have all of them an $E(B - V)$ lower than 0.1.

The interstellar extincion law in the far ultraviolet is not yet well known due to the few stellar observations carried out at this wavelength range. An extrapolation of the interstellar extinction law of Cardelli *et al.* (1989) has been confirmed to be valid by Voyager and HUT observations (Snow *et al.*, 1990; Buss *et al.*, 1994). This extinction law is a function of the ratio of total to selective extinction (R_v) in the star direction, of the form

$$A_\lambda / A_v = a(x) + b(x)/R_v$$

which in the FUV is strongly affected by the value of this parameter R_v. This law has been obtained with observations from the IR to the far-UV at 1000 Å, and need further confirmation at shorter wavelengths.

Therefore the accuracy in the knowledge of the color excess is much more critical in the FUV than in the visible for a precise correction of the interstellar extinction. The stars observed by EURD are very bright and well known objects with accurate observations in the visible and near infrared, therefore not only the $E(B - V)$ can be accurately known but a direct estimation of the value of R_v is possible for many of them from the IR photometry of the JP11 photoelectric catalog (Morel *et al.*, 1978) and the Whittet and Breda (1980) mean relation:

$$R_v = A_v/E(B - V) \approx 1.1E(V - K)/E(B - V)$$

5. Comparison with Model Atmospheres

In this section the obtained spectral energy distribution of the stars observed by EURD is compared with Kurucz model stellar atmospheres (ATLAS 9). These models reproduce the optical and ultraviolet (IUE range) fluxes of B stars, but beyond 1000 Å more work is necessary to fully assure their validity. For this purpose we have taken from the INES Database the best quality observations of the short and long wavelength IUE spectrographs for every star, scaled to them the corresponding Kurucz model and compared the model extension to the far ultraviolet with our observations. A good agreement between model and observation has been found for α Vir (Morales *et al.*, 2000) and the study of the other stars is in course.

At this step it is important to carefully select the adequate model atmosphere for each star, because the gravity and the abundance of elements heavier than helium relative to solar (z) strongly influences the fluxes of model atmosphere calculations at this wavelength range. The FUV range is very sensitive to stellar metalic abundance for late B stars, as an example we can see in Figure 3a Kurucz models of 13000 K temperature for solar composition and two extreme values of z

($\log z = +1, -1$). The differences between the three models is noticeable also at IUE wavelengths, but at EURD wavelengths the difference in flux could be as high as a factor of three for a star of this temperature. Also the effect of gravity is two to three times stronger in the FUV than in the visible, and in the opposite direction, particularly for early B-type stars (Figure 3b).

Individual reddenings have been obtained with the best $(B - V)$ colors from the SIMBAD Database and the intrinsic $(B - V)_0$ colors corresponding to the spectral type from Schmidt-Kaler (1982). Spectral types were taken also from the SIMBAD database.

IUE short and long wavelength spectra for every star were merged at 1940 Å and the resultant IUE spectra were used to fit Kurucz model atmospheres of different temperatures, by steps of 100 K (centered in the temperature corresponding to the spectral type of the star). For every temperature we computed the sigma of the fit and selected the temperature that produces the best fit.

The normalization of Kurucz models to IUE spectra gives us a value of the angular size of the star. All our stars have been observed by the Hipparcos satellite, therefore we can check if the stellar angular size obtained with the best fit reproduces the mean value of the radius expected for the spectral type of the star, using Hipparcos value of the distance.

The values of the sigmas of the fits in a range of temperatures of ± 1000 K around the best fit, confirm that as the stellar temperature increases, the IUE wavelength range is less sensitive to temperature changes (Kurucz, 1979; Longo *et al.*, 1989).

In Figure 4 we show the Kurucz model that best fit the IUE range of the B2IV star HD 157056, and its IUE and EURD spectra.

6. Conclusions

EURD capability to detect stellar emission of B stars is demonstrated. High quality spectra for 9 stars have been obtained so far. Spectra of α Vir give absolute fluxes similar to those obtained by Voyager and those expected from Kurucz models. This confirms the accuracy of the calibration of the EURD spectrograph.

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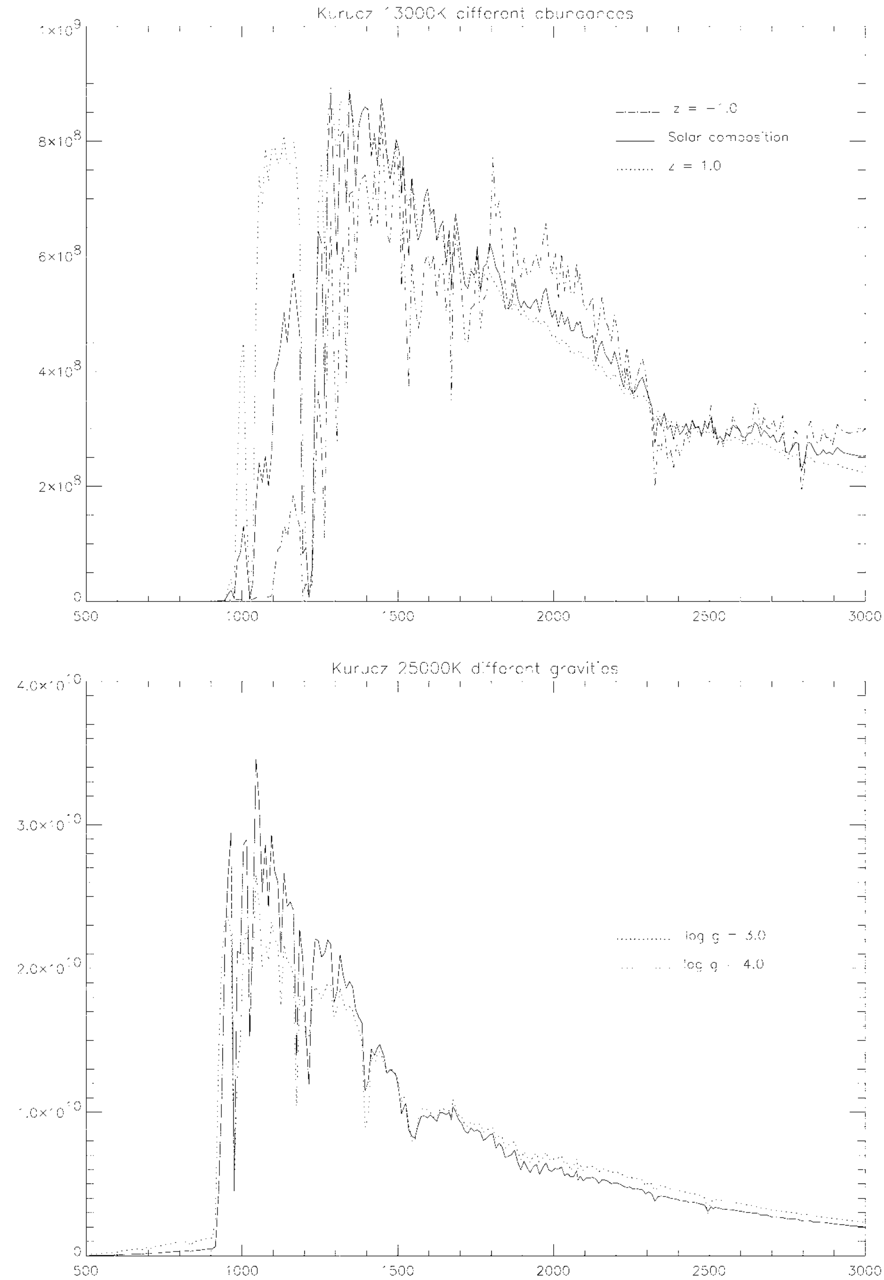

Figure 3. ATLAS9 Kurucz models with different gravities and metallicities.

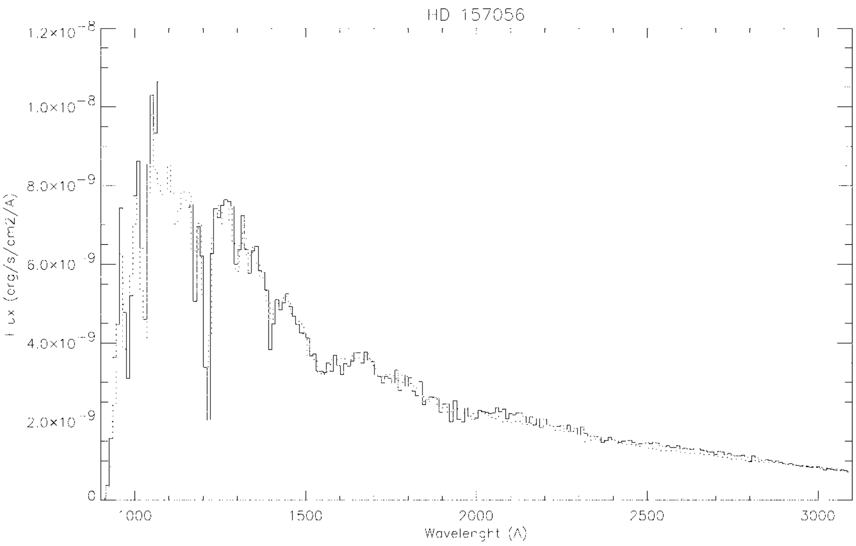

Figure 4. Spectrum of HD 157056 as observed by EURD and IUE (heavy lines) superposed on the Kurucz model normalized to the IUE spectrum (dotted line).

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