Toward Mapping the UV Circumstellar Shells of Late-Type Stars

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Abstract We report detection of spatially resolved circumstellar matter surrounding selected cool stars, using off-source observations made with the International Ultraviolet Explorer satellite. The data demonstrate that: (a) the instrumental scattered light profile of IUE appears to depend on the ultraviolet color temperature of the star observed, and (b) certain red stars show signal in excess of the instrumental levels, at spatial offsets of 10 to 20 arc-seconds from the star.

INTRODUCTION

More than a decade ago, an important observation was published by Bernat and Lambert (1976), wherein the resonance lines of neutral potassium, K I ($\lambda$7699 Å) were detected in emission and mapped over distances of up to 5 arcseconds away from the red supergiant star, $\alpha$ Orionis. This result has been extended by Honeycutt, et al. (1980) and Mauron et al. (1984) to distances of an arc minute. Glassgold and Huggins (1986) used these results in constructing models of the ionization structure of the CSE. It occurred to us that compared to neutral potassium, the ultraviolet resonance lines of Mg II should be far better tracers of the circumstellar matter because of larger abundance and its majority ionization state. Furthermore, the 10 by 20 arcsecond large aperture of the IUE satellite spectrograph could ideally sample the regions described by the K I studies. It has been commonly believed that the instrumental scattered light in the optics of the IUE satellite is too large to permit much in the way of direct detection of faint circumstellar scattering in most stellar sources. In this paper, we report that certain types of low surface temperature stars, including $\alpha$ Ori and $\tau$ Ceti, appear to exhibit intrinsic signal above the instrumental background.

OBSERVING TECHNIQUE and DATA ANALYSIS

We made off-source observations of selected stars, under IUE programs OD14Y, CSJRS, CMKRS and PHCAL. As described in NASA IUE Newsletter 32, spacecraft fine pointing is achieved by use of a Fine Error Sensor (FES). Our
observing strategy was to introduce an additional offset from the FES reference point, prior to the offset to the spectrograph aperture center. In this way, the star is positioned with the desired offset from the center of the aperture, to an accuracy of about \( \pm 1 \) arc second. For example, an additional 77 FES unit offset along the -x axis would leave the star 20 arcsec from the center, or 10 arcsec beyond the edge, of the 10 \( \times \) 20 arcsec aperture, along its long axis.

We rediscovered how to observe with the minimum instrumental scattered light, by: (1) avoiding the diffraction spikes, and (2) using negative FES offsets, so as to place the star below the aperture on the slanted FES aperture plate. Item 1 is best accomplished by offsets along the FES x axis (cf. Carpenter et al. 1987). Item 2 constrains the offsets to the -x direction, yielding scattered light reductions of 50\% (Witt et al. 1982; Stencel et al 1988a). Note that off-source exposures need to be much longer than on-source ones, typically with an exposure time ratio proportional to the offset (in arc-seconds) cubed.

We used with the spatially resolved, line by line files provided as part of the IUE Guest Observer data products. In such files, scans along the spectral dispersion are provided at approximately one arc-second spatial intervals across a swath of image including both large and small apertures and background regions. We used the standard IUE RDAF routine, called LOW, for low dispersion spectra analysis, to extract, calibrate and plot sections of each image. LOW specifically allows each scan line to be separately examined, or in default mode, to produce a merged, calibrated spectrum of on-source exposures.

To facilitate comparison with the results of the K I scattering experiments of Honeycutt et al. (1980) and Mauron et al. (1984), we express the fractional scattered light in terms of \( I(\text{shell})/F(\text{star}) \) (units arcsec\(^{-2}\)), where \( I(\text{shell}) \) [ergs cm\(^{-2}\) s\(^{-1}\) \( \text{Å}^{-1} \) arcsec\(^{-2}\)] is the off-source intensity, and \( F(\text{star}) \) [ergs cm\(^{-2}\) s\(^{-1}\) \( \text{Å}^{-1} \)] is the on-source, spatially integrated flux.

For the IUE observations, \( F(\text{star}) \) is obtained by integrating, at each wavelength, the on-source pixels over the instrumental point spread function (which corresponds roughly to 9 arcsec\(^2\) for IUE images). This is effectively the same as the IUESIPS extraction algorithm. \( I(\text{star}) \) is derived directly from the individual line in the line-by-line image: because averaged pixels in each scan line correspond to approximately 1 arcsec\(^2\), then the individual scan line's monochromatic flux number yields the intensity in units of arcsec\(^{-2}\). After subtraction of a background signal determined from neighboring pixels, the ratio of these numbers then gives us the required fractional scattered light \( I(\text{shell})/F(\text{star}) \) for comparison with earlier work.

**Color dependence of the off-source spectra**

Heretofore, the standard for scattered light calibration in IUE has been the B3 V star, \( \eta \) UMa (Witt et al. 1982. Our initial analysis of the off-source signal surrounding the M supergiant star, Betelgeuse (\( \alpha \) Ori), showed it to be less than that for \( \eta \) UMa. This paradox prompted us to pursue observations of a cool star with negligible mass loss for scattered light re-calibration: \( \epsilon \) Eri (G8 V). In a comparison of the normalized net signal \( I_{\text{off-source}}/F_{\text{on-source}} \) for
both calibration stars at different offset positions, it is obvious that the red star exhibits an order of magnitude weaker signal at all positions larger than about 5 arcsec offset from the target. It appears that the magnitude of the instrumental scattered light in the IUE optics depends on the ultraviolet color temperature of the star observed. One possible explanation for this curious result may be the effect of in-order scattered light from shorter or longer wavelengths, which would depend on the relative far UV or blue-visible flux of the star, and hence the color temperature. To attempt to verify this result, we undertook scattered light observations of the hot dwarf, $\mu$ Col [O9.5 V] and the cool dwarf, $\tau$ Ceti [K2 V]. Note that $\mu$ Col is the primary target for on-orbit calibration of wide angle scattering for the GHRS on Hubble Space Telescope. To the accuracy of the flux calibrations, $\mu$ Col agrees with $\eta$ UMa. The results for the red dwarf stars are discussed below.

**Target Stars**

The observed fractional scattered light in $\alpha$ Ori [M2 Iab, Betelgeuse] runs above both the $\eta$ UMa and $\mu$ Col profiles. Adopting the $\epsilon$ Eri signal as the more suitable calibration star for scattered light around cool stars, the implication is that $\alpha$ Ori [Betelgeuse] has considerable excess signal above the calibration star, for distances less than $\sim$15 arcsec, indicating that the observed light arises from circumstellar as well as instrumental scattering. That the on and off source spectra appear similar strongly indicates that a continuous opacity source, such as dust, is responsible for the off-source intensities in this star. Our IUE results smoothly extrapolate onto the off-source intensities of the earlier scattering work using the K I resonance lines (Honeycutt et al., 1980; Mauron et al. 1984). Note also that ratioing the entire on-source spectrum with those obtained off-source reveals a small excess of Mg II emission. Inspection of the photowrite confirms the ratio result, in the sense that, on-source, the Mg II k/h line strength is 2:1 (as often seen with late type giants), but off-source, the ratio decreases to roughly 1:1. This can be interpreted as a change from resonance line scattering in an optically thick to optically thin environment. The indication for numerous Mg ions at large circumstellar distances is consistent with radio observations that suggest an extended region of free-free emission (Drake 1987).

We also observed the K giant Arcturus, with the intention of acquiring additional calibration data on instrumental scattered light. The current mass loss rate for Arcturus is estimated to be $10^{-4}$ times that of Betelgeuse. However, the data suggest that Arcturus too has excess Mg II signal and is also surrounded with a large scattering envelope, as indicated by the fractional scattered Mg II light excess compared to $\epsilon$ Eri. The original data suggest the just resolved Mg II k/h feature ratio is varying off source, suggesting resonance line scattering processes, although the lack of offset between Mg II and continuum suggests a continuous opacity source. Drake (1985) predicted that the ionized wind should have visibility to $\sim$50 stellar radii, which is $\sim$1 arcsec at Arcturus' distance.

The binary $\alpha$ Sco [Antares, M2 Ib + B3 V] is also in excess of the $\epsilon$ Eri profile, but not significantly with respect to the $\eta$ UMa one. Inspection of
the spectra show that the on-source hot star continuum spectrum gives way to chromospheric emission line spectrum (Mg II, Fe II) off-source. It seems this dramatic change in the spectral character is a phenomenon which cannot be explained by instrumental scattering alone, and must reflect scattering of M star light in the CSE.

In an attempt to confirm the remarkably low level of scattered light surrounding the G8 V star, ε Eri, we observed the K2 V star, τ Ceti using similar offsets, as part of a PHCAL shift in late June 1989. To our surprise, the signal was considerably above that expected based on ε Eri. We have no explanation for this, assuming the data were correctly obtained, other than the possible serendipitous discovery of an extended cometary cloud, as suggested by Stern (1990). This pronounced difference deserves further study.

CONCLUSIONS

Based on the preceding, it appears the technique of off-source ultraviolet observations for the mapping and direct analysis of the circumstellar environments of cool stars holds considerable promise. However, several observations and measurements are needed to secure the conclusions listed above. First, selection and observation of additional early and late type main sequence stars with negligible mass loss, to serve as point source/scattered light calibration checks on targets discussed herein. The acquisition of additional off-source data for these objects with IUE would be of great value in understanding the scattered light characteristics of both IUE and HST telescopes and spectrographs. Second, additional evaluation of the "slit function" of the oval shaped apertures may be necessary to determine whether some degree of vignetting is reducing the signal on the brighter portion of the off-source exposure data. However, we anticipate this will amount to only a first order correction on the results presented here.

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