UXORs: A Unique Opportunity to Study Disk Structure

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B. Rodgers
Gemini Observatory, Gemini-South, AURA/Chile
P.O. Box 26732, Tucson, AZ 85726

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UXORs: A Unique Opportunity to Study Disk Structure

Bernadette Rodgers

Gemini Observatory, Gemini-South, AURA/Chile, P.O. Box 26732, Tucson, AZ 85726; brodgers@gemini.edu

Abstract. What distinguishes UXORs among the seemingly ubiquitous photometric and polarimetric variability of pre-main sequence stars, is the magnitude of their variations (i.e., $\Delta V > 1.5$, $\Delta p \gtrsim 2\%$). If occultation by circumstellar disk material is the cause of the variability in these stars, these obscuration events provide an opportunity to study the structure and behavior of disks through the effects they have on the starlight.

Spectral monitoring of the UXOR star RR Tau (Rodgers *et al.* 2002) shows that variability across the optical spectrum is well-correlated with the photometric changes and allows us to place constraints on the size of obscuring material. With more detailed modeling, these kind of data have the potential to probe in detail how the circumstellar gas is effected and/or implicated in the variability known as the "UXOR phenomenon".

1. Introduction

The so-called UXOR-type or UXOR stars are a highly variable subset of Herbig Ae stars, pre-main sequence stars of intermediate mass, named after the prototype object UX Ori. The nature of UXORs is a matter of on-going debate, but one possibility is that they are young systems viewed through some portion of their circumstellar environment that occasionally obscures the central star. If this is the case, detailed study of the photometric, polarimetric and spectroscopic variability of these systems during occultation events can reveal information about the occulting material and hence, the circumstellar disks.

At the conference, my talk was divided into two parts: UXOR properties in general, and results of a spectroscopic monitoring program of the UXOR star RR Taurus. Since the latter are already published (Rodgers et al 2002; hereafter RWGSN), a large fraction of this space is devoted to the unique properties of UXORs (Section 2), followed by a brief summary of RWGSN (Section 3).

2. What is a UXOR Star?

The harder one looks for a quantitative answer to this question, the more elusive it becomes. According to Grinin *et al.* (1991), UXORs are generally Herbig Ae stars that exhibit 1) "occasional nonperiodic minima with amplitudes $\Delta V \simeq 1-3$ mag"; 2) increased linear polarization during minima; and 3) a "blueing" effect or color turnaround such that after initial reddening the star becomes bluer in

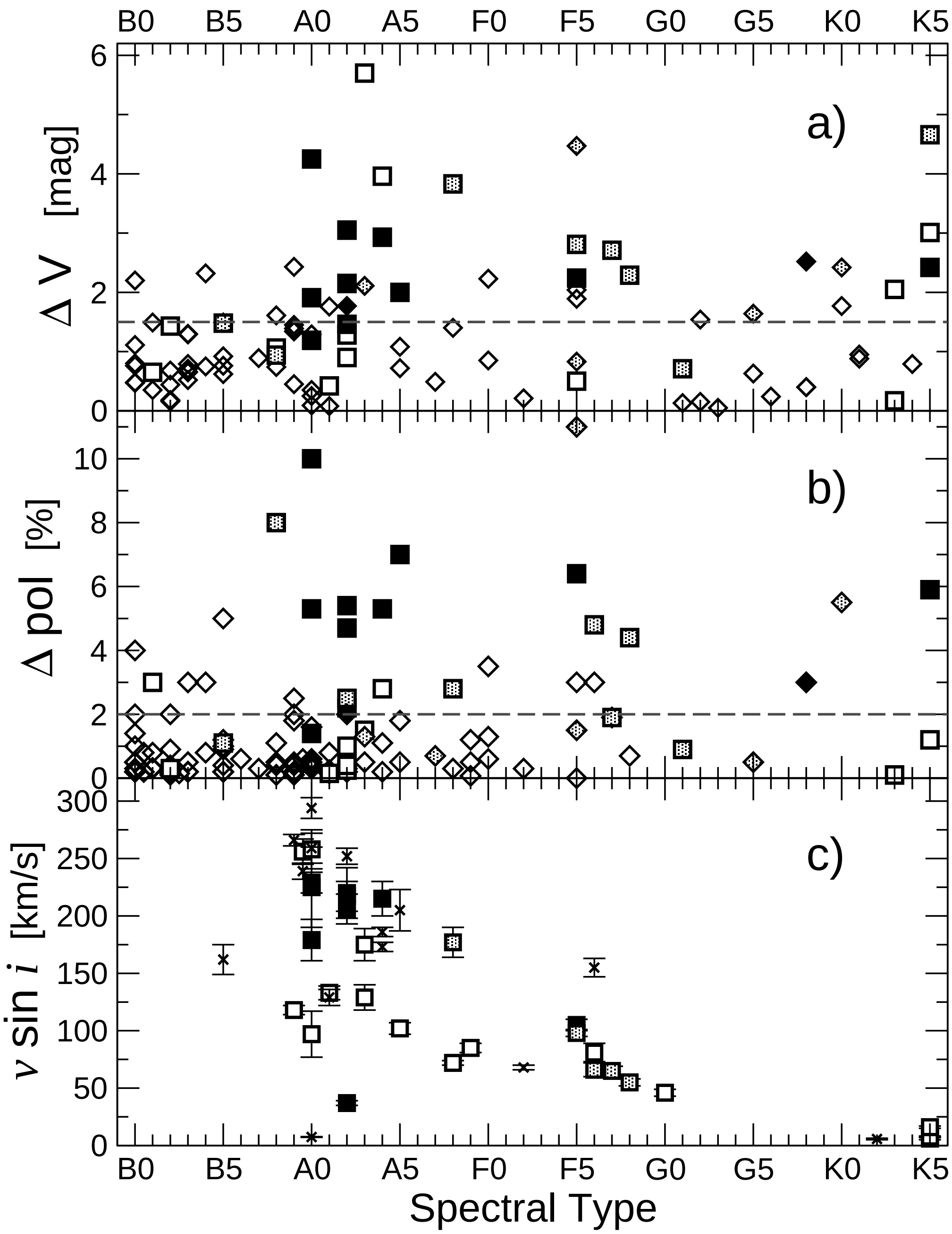

Figure 1. Pre-main sequence stars: Spectral type vs. a) Range in V magnitude from the compilation data of Herbst&Shevchencko(1999, HS); b) Range in linear polarization from the compilation of Yudin (2000); c) $v$sin$i$ measured by Mora *et al.* (2001, MMS). In all panels, solid symbols are "known UXORs", shaded symbols are "possible UXORs" (see text). Spectral types from MMS shown as squares, other sources (Yudin, HS or SIMBAD) are diamonds. Crosses in panel c are main sequence stars from MMS. Horizontal lines are drawn at $\Delta V = 1.5$ and $\Delta p = 2$ (see text). (The two high ΔV open squares in panel a are T Ori and V1686 Cyg.)

$B-V$ at deepest minima. They attribute (1) to the star being "covered almost fully by [an] opaque dust cloud intersecting the line of sight", and (2) and (3) follow as a consequence of scattered light from the disk dominating the observed radiation during these occultation events. Note that while the latter two are strong evidence for a circumstellar disk seen at some inclination, they do not strongly constrain the nature of the minima events.

This definition has been blurred in recent years, mainly due to the increase in available data and the propensity for variability in all pre-main sequence stars. Herbst & Shevchenko (1999, HS) suggest virtually all Herbig Ae/Be stars could be considered UXORs, but with a wide range of amplitudes (ΔV). Based on a sample of 42 HAEBE and T Tauri stars, Oudmaijer *et al.* (2001) observe variable linear polarization that appears to be anti-correlated with optical brightness in a number of sources, and suggest several new UXORs, but the range of variability tends to be small ($\Delta V \lesssim 1, \Delta p \lesssim 1\%$). Since all of these systems likely harbor circumstellar disks, this polarization behavior is perhaps not surprising, regardless of the cause of the optical variability. On the other hand, new polarimetry of several well-known UXORs suggests that the correlations may not be so straight-forward (Hutchinson *et al.* 1994).

Figure 1 plots a measure of photometric and polarimetric variability from the literature for a number of pre-main sequence stars. When considering a statistical compilation, it is the nature of variability data to be incomplete. I have attempted to identify "known UXORs" in Figure 1 as those objects [1] that are well-studied or have multiple corroborating data; an additional 18 that have been suggested in the literature based on limited data are labeled "possible UXORs". Note that the datasets differ between the three panels, but with many overlapping objects.

The magnitude of the variability of UXORs is apparent in the top two panels, as is the well-known preference toward spectral types A–F. However, UXORs are only a subset ($\sim 20-40\%$) of Herbig Aes, many low variability objects exist as well. Perhaps a unique aspect of UXORs is that the large values of ΔV and Δp indicate that the scattered light visible at optical minima is not the dominant light source in these systems. The figure suggests these approximate cutoffs between UXORs and non-UXORs: $\Delta V > 1.5$ ($\gtrsim 75\%$ of the optical light disappears) and $\Delta p \gtrsim 2\%$ (remaining light is strongly polarized).

Are UXORs edge-on versions of otherwise "normal" Herbig Ae stars? Natta *et al.* (1997) find no significant differences in age or disk mass between the two groups. Larger linear polarization (Fig. 1b), and higher $v\sin i$ are possible diagnostics of larger inclination systems. Previous attempts have not found any correlation between $v\sin i$ and ΔV (e.g., HS, Yudin 2000), however, inconsistencies between measurements and intrinsic scatter may have been factors. The bottom panel of Figure 1 plots the recent $v\sin i$ data of MMS for 29 pre-main sequence stars (including 8 known UXORs) and 15 main sequence stars. In this dataset the tendency toward higher values for the UXOR stars is clear (although not without exception).

[1] BF Ori, CQ Tau, RR Tau, SV Cep, UX Ori, VV Ser, VX Cas, WW Vul, VY Mon, V586 Ori, RY Lup and BM And

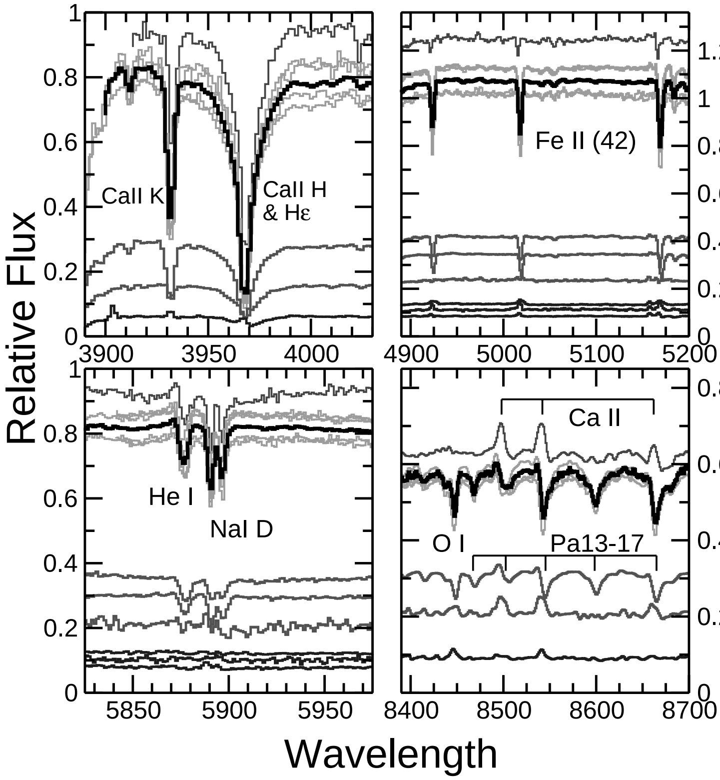

Figure 2. RR Tau spectra showing circumstellar metal lines in relative flux units (RWGSN, Fig. 10). Thick line is average of 5 bright spectra (also shown). Strong absorption seen at maximum light is replaced with weak emission in faintest epochs.

3. Spectral Monitoring and Results for RR Tau

Just as polarimetric monitoring of these systems has provided valuable new information, spectral monitoring, so far very limited in the literature, also has the potential to provide details of the behavior of the gas not accessible from photometric data alone.

Results of a spectral monitoring program of the UXOR star RR Tau are presented in RWGSN. In a collection of 12 spectra taken over two observing seasons and spanning a factor of 10 in optical brightness ($11 \lesssim V \lesssim 13.7$), we find the equivalent width (EW) behavior of the lines are clearly correlated with the photometric behavior. This behavior falls into three categories: lines with constant EW, lines of constant flux (increasing EW with fading continuum) and lines whose EW varies from absorption to emission as the star fades. The first group consists of photometric features (metal lines and the wings of the balmer lines) which change with the continuum; the second group are strong emission lines primarily associated with a stellar wind ([OI], Hα) and largely unaffected by the minima events. The third group, shown in Figure 2, are low-ionization metal lines from circumstellar gas. We show in RWGSN that these lines can be de-composed into dueling components of the other two types: strong absorption lines of constant equivalent width, which dominate during bright epochs, and weak emission lines of approximately constant flux, which only become visible when the continuum drops significantly.

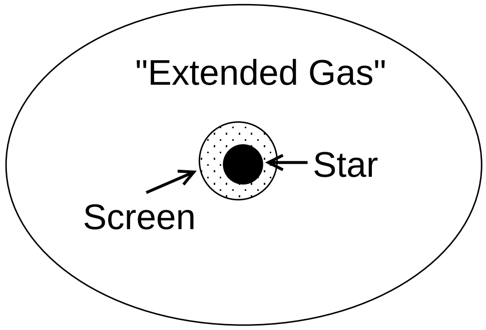

Figure 3. Cartoon of an obscuration event, showing constraints on the relative size of the screen as deduced by RWGSN: $R_* \lesssim R_{screen} << R_{env}$, where R_{env} represents the region of extended emission, from a disk or otherwise (not drawn to scale).

In the context of the obscuration model, we speculate that the absorbtion originates in optically thick gas close to the star that is occulted with it, while the weak emission arises from extended gas that is essentially unaffected by the occultation events. This conclusion allows us to constrain the physical extent of the occulting screen, as depicted in Figure 3. Note that, despite the figure, our interpretation constrains only the size and approximate location of the optically thick material but says nothing about its nature or morphology.

4. Conclusion

The model developed in RWGSN is very simplistic and not necessarily physically realistic (particularly in the company of the beautiful, sophisticated models elsewhere in these proceedings!). However, what I have hoped to convey here is

- UXOR stars are a unique subset of pre-main sequence stars, worthy of further study and better modeling;
- Correlated spectral and photometric variability clearly show the behavior of some gas emission is linked to the photometric variability; and
- Spectral monitoring (and modeling) can provide detailed information on the nature of circumstellar activity during these optical minima events.

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