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NEAR IR TiO BAND PHOTOMETRY OF α Ori, 1996-1997

α Orionis (Betelgeuse, HD 39801, M2Iab) is the brightest star in the infrared sky. It is also one of the closest, with the recent *Hipparcos* Survey revising its distance determination to 131 ± 30 pc (Wing 1997). The star's relative proximity, coupled with its semi-regular variability and advanced evolutionary age, has made it an attractive target for a number of studies. For example, Guinan *et al.* (1993) have reported an overall photometric variability of 0.45 mag over the last decade, while Dupree *et al.* (1987) have found a 1.15 yr periodic modulation of 0.26 mag in blue wavelengths that stretches back to 1984. Gilliland and Dupree (1996) have used direct imaging techniques with HST to uncover a substantially extended chromosphere in the supergiant as well as a large bright spot that appears hotter than the surrounding chromosphere by at least 200 K. Dyck *et al.* (1992) have even used 2.2 μm interferometric techniques to obtain an angular diameter for α Ori of 44.2 mas. This corresponds to a radius of 620 $R_\odot$.

Despite these studies, α Ori remains an enigmatic object. There is still some question as to the proper mass loss mechanism that can form the star's extensive circumstellar envelope (Dupree *et al.* 1987). Furthermore, the period of pulsations may not be constant with time. There is also evidence of period-doubling and period-tripling in the star's visible flux (Smith 1990) that hints at the star's internal complexities. Optical wavelength observations of α Ori have continued up to the present by Krisciunas & Luedeke (1996) and at Villanova University by Guinan (1997) since 1981, but have shed little light on these stellar riddles. To understand and better quantify the behavior of α Ori, we decided to undertake a more extensive program of differential photometry of this famous star.

From September 1996 to April 1997, α Ori was observed at the Wasatonic Observatory (Allentown, Penn.) as part of the ongoing program between the Wasatonic and Villanova Observatories to study cool giants and supergiants. The photometry reported here was conducted on a total of 23 nights using an uncooled Optec photometer attached to a 20-cm Schmidt-Cassegrain telescope. The detector employed was a silicon PIN-photodiode. The comparison star was Φ^2 Ori (V = +4.09, B−V = +0.95, K0III) and the check star was γ Ori (V = +1.64, B−V = −0.22, B2III). Differential photometry was conducted using the standard sequence of sky-comp.-var.-comp.-sky-check-comp.-sky in both the V-band and Wing near-IR three filter system to measure TiO (Wing 1992).

Wing's photometric system is characterized by observations in three separate bandpasses denoted by A, B, and C. Table 1 lists the central wavelengths and bandwidths of these three filters. These filters were chosen to measure the three basic properties of cool stars: their infrared magnitude, their color, and their temperature (as measured by the strength of their TiO absorption band). Filter A is sensitive to the TiO $\gamma(0,0)$ 719 nm bandhead, while filters B and C are essentially clear of strong absorptions. In order to extract an unreddened measure of the strength of the TiO band, Wing (1992) has devised a reddening-free TiO index as: $A - B - 0.13(B - C)$

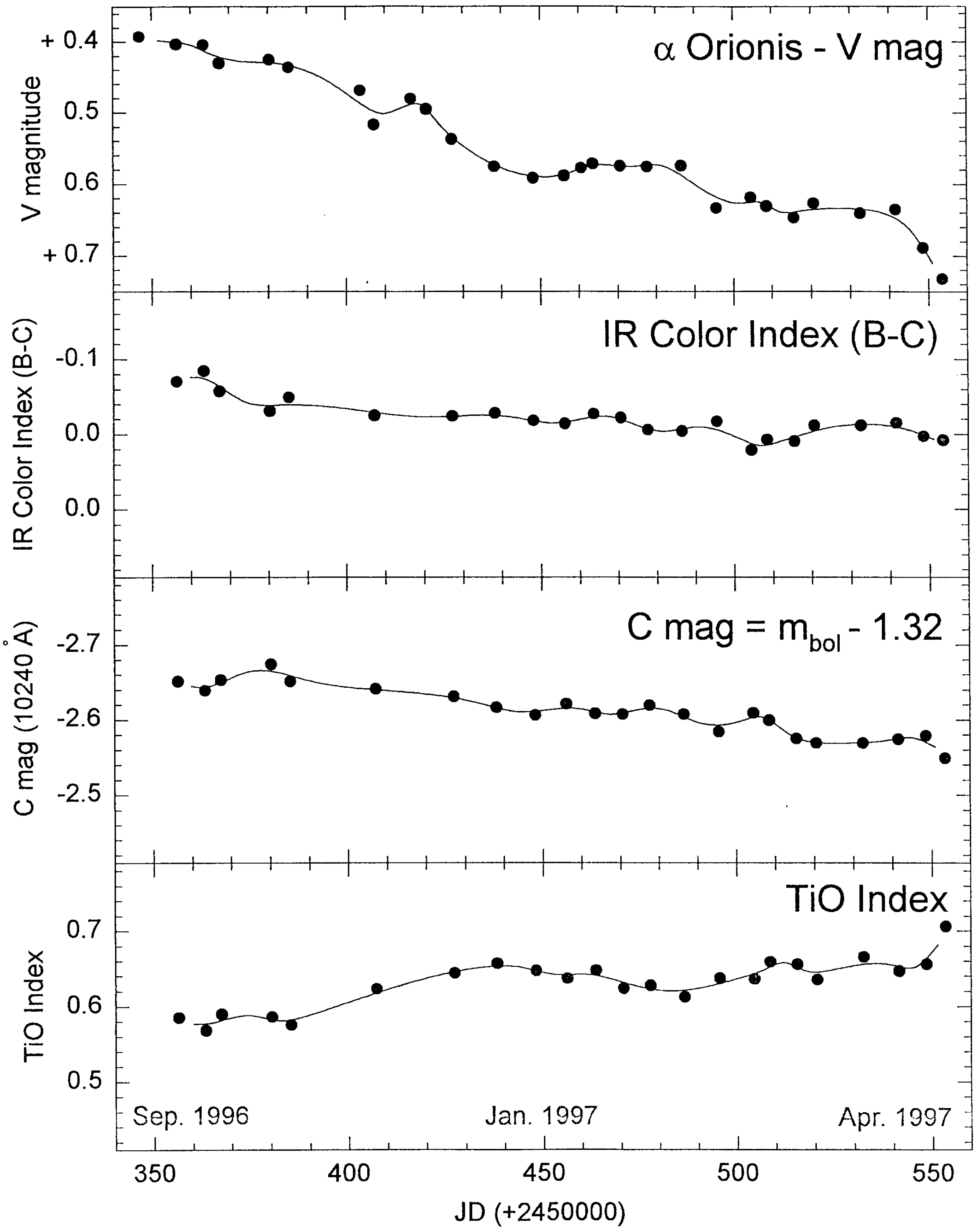

Figure 1. The 1996-1997 V-band and near IR observations of α Ori. The top panel shows α Ori's V-band light curve over the observation period. The star's IR color index and C(1024) magnitude light curves are shown in panels 2 and 3, respectively. The bottom panel is a plot of TiO indices as defined by Wing's three color filter system. Note the inverse correlation between TiO strength and brightness of the star

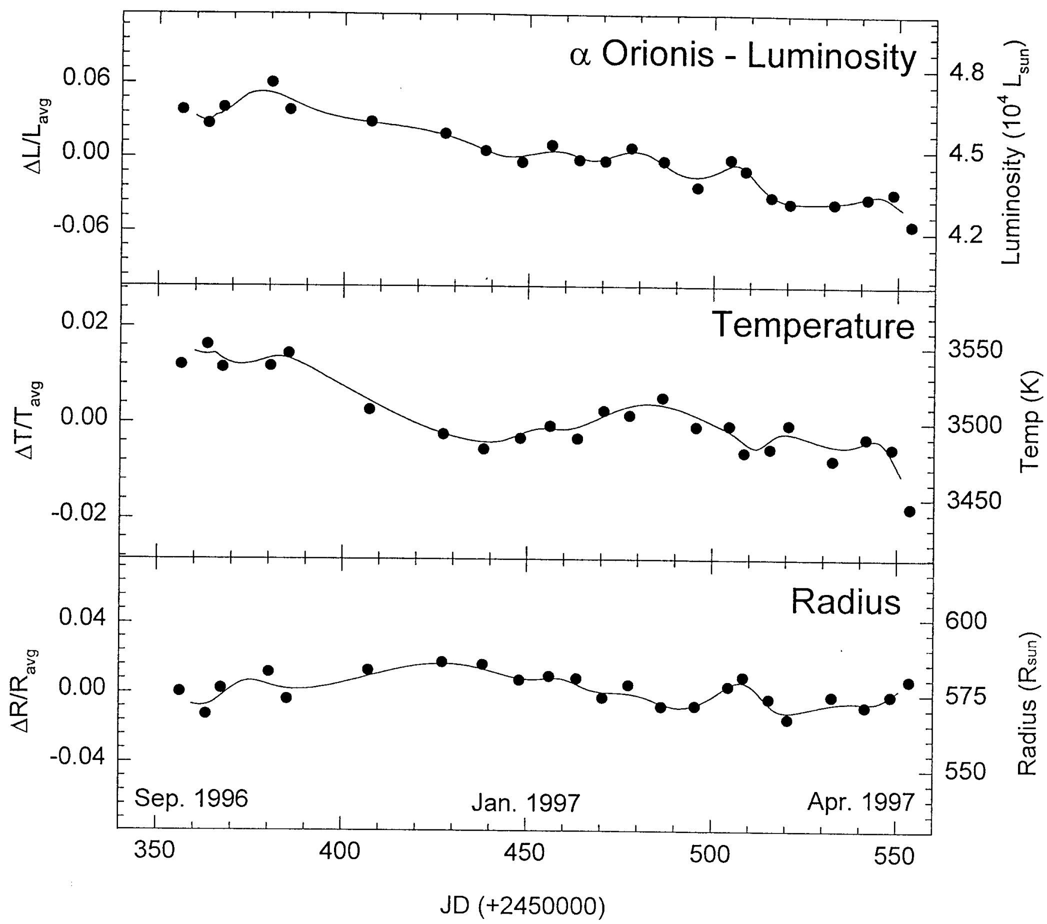

Figure 2. Results for α Ori for the 1996-1997 observation period. The top panel shows the star's luminosity. The middle panel shows α Ori's temperature as derived from TiO indices. The bottom panel depicts α Ori's radius over time based on a symmetric, global pulsation model

Table 1. Wing's Three Color Near IR Filter Set[1]

Filter	Region Measured	Central Wavelength (nm)	Bandpass(FWHM) (nm)
A	TiO Band	719	11
B	Continuum	754	11
C	Continuum	1024	42

[1]Taken from Wing (1992)

where A, B, and C are the magnitudes in those respective filters. The quantity (B−C) is defined as the star's near IR color index. Wasatonic (1997) has provided a calibration system based on standard stars (Wing 1978) that relates TiO strength to a star's temperature. The result is an inverse correlation between temperature and TiO index for K5 to M7 stars shown below:

$$Temp(K) = 3990 - 775(\text{TiO-Index})$$

Table 2. Wasatonic Observatory Filter A,B,C Data for α Ori: Sep 1996–Apr 1997

JD (2450000+)	A	B	C	JD (2450000+)	A	B	C
356.328	−2.145	−2.721	−2.651	477.622	−1.998	−2.625	−2.619
363.303	−2.166	−2.723	−2.639	486.506	−1.999	−2.611	−2.607
367.382	−2.128	−2.710	−2.653	495.540	−1.966	−2.601	−2.584
380.312	−2.123	−2.705	−2.674	504.507	−1.949	−2.588	−2.609
385.218	−2.131	−2.700	−2.651	508.526	−1.932	−2.592	−2.599
407.194	−2.046	−2.666	−2.641	515.522	−1.909	−2.566	−2.575
427.197	−2.014	−2.655	−2.631	520.616	−1.947	−2.581	−2.569
438.127	−1.991	−2.644	−2.616	532.555	−1.917	−2.581	−2.569
448.084	−1.979	−2.624	−2.606	541.555	−1.944	−2.589	−2.574
456.146	−2.000	−2.635	−2.621	548.555	−1.920	−2.576	−2.579
463.533	−1.991	−2.635	−2.608	553.555	−1.834	−2.541	−2.549
470.592	−2.008	−2.629	−2.607				

It should be noted that this relationship fails outside the specified spectral classes since TiO band strengths are insensitive to temperature changes outside of the K5 to M7 range.

The bolometric magnitude (m_{bol}) of the star can also be approximated using the Wing system. Filter C is an accurate measure of an M star's near-infrared continuum and covers their wavelengths of peak intensity. Furthermore, it is known that near-infrared continuum points of Mira variables are very similar to their bolometric light curves in terms of shape, phase and amplitude (Lockwood & Wing, 1971; Wing 1986). Hence the magnitude of filter C is a good representation of the star's apparent bolometric magnitude. Using bolometric corrections from Novotny (1973), we compared the apparent m_{bol} and C(1024) magnitudes of stars with comparable temperatures to α Orionis. A total of eight M2III Wing standard stars (Wing 1978) were used in the comparison. Since bolometric corrections are nearly identical for M2 giants and supergiants (Novotny 1973), we found that for both classes of stars:

$$m_{bol} = C + 1.32$$

where C represents the magnitude of the C(1024) filter. This magnitude correction has a standard deviation of $\sigma = 0.075$. The luminosity of the star can then be calculated from its m_{bol} by the usual means.

The data collected at the Wasatonic Observatory is listed in Table 2. Observations were conducted in both V-band and Wing's three color filter system with light curves shown in Figure 1. The first panel shows a plot of α Ori's V-band light curve. α Ori dropped 0.3 mag in V-band brightness over the observation period. The maximum brightness of +0.4 mag is about the brightest the star ever achieves (Guinan 1997). Light curves of the star's near IR color index and C(1024) magnitude are shown in the second and third panels, respectively. The small-scale fluctuations in the data appear to be physical variations and are not observational scatter. TiO indices were then calculated using the Wing system described above and are shown in the bottom panel of Figure 1. Note the general anti-correlation between TiO band strengths and the brightness of the star.

Figure 2 summarizes our results based on the near IR data. The top panel shows α Ori's luminosity, the middle panel its effective temperature, and bottom panel its effective radius over our observation period. The left axis of the figure shows relative changes with respect to the mean, while the right axis shows absolute values. As shown in the top panel, α Ori's luminosity systematically dropped approximately 12% with respect to the mean over our observation stretch. This was accompanied by a 4% systematic drop in effective temperature during the same time interval. Based on our TiO data, α Ori showed an average effective surface temperature of 3500 K. The maximum and minimum temperatures were 3550 K and 3440 K, corresponding to TiO indices of 0.568 and 0.706, respectively. These temperature values agree well with the interferometric estimated surface temperature of 3520 ± 85 K by Dyck *et al.* (1992).

It is still uncertain whether the luminosity changes shown in the top panel of Figure 2 are due to uniform, global pulsations of the star, or the growth and decay of local hot-spots on the surface. Goldberg (1984) concludes from radial velocity data that the visual brightness variations are probably not global in nature. However, Dupree *et al.* (1987) assert that the regularity of α Ori's variability argues against the erratic (random) variability associated with the emergence of convective cells. Under the assumption that the luminosity variations are global in nature, the effective radius of α Ori was computed for each observation. The result is shown in the bottom panel of Figure 2.

α Ori exhibited an average effective radius of 575 $R_{\odot}$ with changes of less than 2% above and below the mean radius over the observation period. This value compares with past interferometric radius determinations. For instance, Dyck *et al.* (1996) used 2.2 μm observations to obtain an angular diameter of 44.2 mas, corresponding to a radius of 620 $R_{\odot}$, and Balega *et al.* (1982) have used 7730 Å observations to obtain an angular diameter of 62 mas, corresponding to a radius of 870 $R_{\odot}$. This paper's result, however, represents the first findings of α Ori's radius using intermediate infrared observations and the new *Hipparcos* distance.

Curiously, there appears to be no systematic change in α Ori's effective radius to match the trends discussed above for α Ori's luminosity and temperature. This might indicate that global pulsations are not alone responsible for α Ori's brightness variations. Instead, the growth and decay of local blobs and hot-spots may contribute to α Ori's variability in a non-trivial way. More near IR and radial velocity data is needed before any permanent conclusion can be reached. It should also be noted that our absolute luminosity and radius values critically depend on the empirically derived transformation between the C(1024) filter and bolometric magnitude. Further observations of M2I and III stars using Wing's near IR filter system would improve the reliability of this transformation. Observations of α Ori at the Villanova and Wasatonic Observatories will continue in both V-band and near IR wavelengths.

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