Session I

Observations of Non-spherical Winds

chair: J.M. Marlborough and P. Williams

Rotationally Modulated Winds of O Stars

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Abstract. The stellar wind diagnostics of some well-studied O stars exhibit cyclical variations with periods that are probably related to the rotational period of the underlying star. This rotational modulation is usually attributed to large scale, persistent structures in the wind, which are thought to be generated and maintained by photospheric processes that alter the emergence of the wind from different regions of the stellar surface. In this review, three case studies are used to illustrate the patterns of variability that are attributed to rotational modulation and to highlight some open issues connected with this hypothesis. The problems associated with establishing the occurrence of rotational modulation rigorously are also discussed.

1 Introduction

Intensive ground- and spaced-based spectroscopic monitoring programs have shown that the stellar winds of luminous OB stars vary systematically on time scales that are longer than their estimated flow times; see, e.g., the contributions to this Colloquium by Kaufer, Kaper, and Massa. Often these variations have a cyclical component; in a few well-studied cases, the time scales associated with these cycles can be related to the estimated rotational period of the underlying star. Consequently, rotation is now believed to be one of the main processes controlling the variability of hot-star winds. Much of the observed variability is attributed to the presence of large-scale structures in the stellar wind, which persist for many rotational cycles and alter the wind diagnostics seen by a distant observer as they are carried around the star. These structures are presumably maintained by photospheric processes that affect the emergence of the stellar wind from localized regions of the stellar surface in some way.

The hypothesis of "rotational modulation" is the focus of many of the contributions to this Colloquium. The purpose of this review is to emphasize some of the difficulties associated with establishing this hypothesis rigorously, and to illustrate the diverse phenomenology currently associated with rotationally modulated stellar winds.

2 Can Rotational Modulation Be Demonstrated?

Rotational modulation can be demonstrated by supplying evidence of cyclical or quasi-cyclical variations in a stellar wind diagnostic (e.g., a P Cygni pro-

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file), and showing that the period associated with these variations is related to the rotational period of the star to within some tolerance. Acquiring evidence for modulation is subject to the constraints imposed by the sampling theorem, weather, or time allocation committees, but is otherwise straightforward. However, demonstrating that an observed period is consistent with the rotational period (or a meaningful fraction of the rotational period) is much more difficult, for two reasons.

First, there are large uncertainties associated with the radius of an individual star. If $R_\star$ is the equatorial radius of the star in $R_\odot$ and $v_{\rm rot}$ is the equatorial rotational velocity in km s^{-1}, then the rotational period in days is

$$P_{rot} = 50.61\, R_\star \,/\, v_{rot} \ . \tag{1}$$

The uncertainty in estimates of $P_{\rm rot}$ is dominated by the uncertainty in measurements of the stellar radius: even in the best cases (e.g., ζ Puppis), this amounts to a fractional uncertainty of $\sim$25%. Consequently, the fractional uncertainty in estimates of $P_{\rm rot}$ will be at least this much for single early-type stars.

Second, this large uncertainty is compounded by the fundamental difficulty in determining the inclination of the rotation axis to the observer's line of sight. Since only the projected rotational velocity, $v_{\rm rot} \sin i$, can be measured, only a upper limit on the true rotational limit can be obtained:

$$P_{\rm rot}^{\rm max} \equiv 50.61\, R_\star \,/\, (v_{\rm rot}\ \sin i) = P_{\rm rot} / \sin i \ . \tag{2}$$

The traditional strategy for overcoming this problem is to limit the investigation to a sample of stars with very similar radii. If the observed periods, $P_{\rm obs}$, are due to rotational modulation, then (2) shows that they are inversely proportional to $v_{\rm rot} \sin i$. Consequently, the generally accepted "proof" that $P_{\rm obs}$ for the whole sample can be attributed to rotational modulation is the demonstration that the observed periods occupy a region of the Period–$v_{\rm rot} \sin i$ plane defined by $P_{\rm obs} \le P_{\rm rot}^{\rm max} \propto (v_{\rm rot} \sin i)^{-1}$. However, this approach is not very useful for O-type stars as a class, since they exhibit a large range in radii. The only alternative strategy, which in fact has guided much of the work for the O-type stars, is to select targets with the largest values of $v_{\rm rot} \sin i$ for their spectral classification. This implies that, in some broad statistical sense, the inclination must be close to 90°.

Since the rotational periods of single O stars cannot be determined precisely, the basic prediction of the rotational modulation hypothesis cannot be confirmed observationally. Instead, ancillary observational evidence must generally be introduced to argue for or against the hypothesis: e.g., the universality of the phenomenon; the constancy and phase stability of the observed period; the presence or absence of multiple periods; the prevalence of related physical processes that can be observed directly. These ancillary arguments often represent model-dependent inferences, which may not be correct. Thus, we are left with the unsatisfying recognition that the hypothesis of rotational

Table 1. Physical parameters for case studies

Quantity	HD 66811		HD 37022		HD 64760	
Spectral Type	O4 I(n)f	(1)	O7 V	(2)	B0.5 Ib	(3)
$\dot{M}$ [$\times 10^{-6}$ $M_\odot$/yr]	5.9	(4)	...		0.1	(5)
$R_\star$ / $R_\odot$	19	(4)	8	(6)	22	(7)
v_∞ [km s^{-1}]	2250	(4)	1600–3600	(8)	1500	(9)
$v_{\rm rot} \sin i$ [km s^{-1}]	219	(10)	53	(10)	216	(10)
$P_{\rm rot}/\sin i$ [days]	4.4		7.6		5.2	
$P_{\rm obs}$ [days]	5.075	(11)	15.422	(2)	1.202	(12)

(1) Walborn 1972 (2) Stahl et al. 1996 (3) Hiltner et al. 1969 (4) Puls et al. 1996 (5) Fullerton & Puls, unpublished (6) Howarth & Prinja 1989 (7) Humphreys & McElroy 1984 (8) Walborn & Nichols 1994 (9) Massa et al. 1995b (10) Howarth et al. 1997 (11) Moffat & Michaud 1981 (12) Prinja et al. 1995

modulation is equally difficult to prove or disprove. If an observed period is within 20 or 30% of the "best-guess" rotation period, then rotational modulation must at least be considered to be a viable explanation for the variations.

3 Case Studies

Despite the difficulties discussed above, there is a growing consensus that the winds of at least some OB stars are rotationally modulated. Here, three well-studied stars that span the range of O-star temperatures – ζ Puppis (HD 66811), θ^1 Orionis C (HD 37022), and HD 64760 – are presented as "case studies" to illustrate the patterns of wind variability attributed to rotational modulation, and to highlight some open issues connected with the hypothesis. Salient parameters for these objects are listed in Table 1.

3.1 HD 66811

The bright, early-type O supergiant HD 66811 = ζ Puppis offers favourable circumstances to search directly for rotationally modulated stellar wind diagnostics because its radius is comparatively well determined from measurements of its angular diameter and distance, and from spectroscopic analyses. Its unusually large value of $v_{\rm rot} \sin i$ suggests that $i \approx 90°$, which therefore implies that $P_{\rm rot} = 4.4 \pm 1.3$ days.

Cyclical variations with period 5.075 ± 0.003 days have been observed in the morphology of both the Hα emission feature (Moffat & Michaud 1981; Berghöfer et al. 1996) and the absorption trough of the Si IV resonance lines (Howarth et al. 1995). Since $P_{\rm obs}$ is within the large uncertainty associated with the measured value of $P_{\rm rot}$, it is attributed to a disturbance in the wind that recurs once per rotation cycle. Both Moffat & Michaud (1981) and

Howarth et al. (1995) suggested that the disturbance is due to the effects of a weak, low-order magnetic field whose axis of symmetry is inclined with respect to the rotation axis (i.e., an oblique magnetic rotator). Such a field will tend to suppress the emergence of the wind from the region near the magnetic equator. However, in order to exhibit only one modulation per rotation, the magnetic geometry cannot be symmetric about its axis, either because of the presence of a quadrapole component or because the dipolar field is offset from the center of the star along the magnetic axis (i.e., a decentered oblique rotator).

The photosphere and wind of ζ Pup also display a host of other periodic variations. Discrete absorption components (DACs) are the dominant component of wind variability, but these recur with a period of 19.2 hours (Howarth et al. 1995), which seems to be unrelated to $P_{\rm rot}$. A soft X-ray period of 16.7 hours (in 1991; Berghöfer et al. 1996) or 15 hours (in 1996; Berghöfer, this Colloquium) is attributed to shock structures in the wind, but apparently these structures are not directly related to $P_{\rm rot}$ or the DACs, though Hα seems to vary with the 16.7-hour period. Deep-seated variations with a period of 8.54 hours have been attributed to nonradial pulsations (NRP; Baade 1988; Reid & Howarth 1996), but this period cannot be linked to the others (except possibly the 16.7-hour X-ray period), so it is not clear that NRP are plausible triggers for the formation of wind structures. Finally, Eversberg et al. (1998) have presented evidence to suggest that the wind of ζ Pup consists in part of stochastically evolving clumps, in addition to large-scale, coherent structures.

Thus, although ζ Pup provides direct evidence for rotational modulation, its wind appears to be subject to a variety of perturbations. Both NRP and magnetic structures are believed to be present, but cannot be directly linked to the large-scale wind structures represented by DACs, the periodic shock phenomena seen in X-rays, or the stochastic evolution of smaller-scale clumps. At the very least, the bewildering array of apparently unrelated variations exhibited by this exceptionally well-studied star cautions against interpreting stellar wind variability in terms of a single process.

3.2 HD 37022

HD 37022 = θ^1 Orionis C is a youthful object situated in the heart of the Trapezium in Orion. It has a history of spectroscopic peculiarities, which include reports of variable inverse P Cygni profiles (Conti 1972) and progressive changes in spectral type from O6–O4 over an interval of about a week (Walborn 1981).

Stahl et al. (1993) detected cyclical changes in the shape and strength of the Hα wind profile of θ^1 Ori C. The period associated with these changes is known very accurately: 15.422 ± 0.002 days (Stahl et al. 1996). The same period has been recovered from the wind profiles of the C IV and Si IV UV

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resonance lines (Walborn & Nichols 1994; Stahl et al. 1996), soft X-ray emission (Gagné et al. 1997), and photospheric line profiles (Stahl et al. 1996). *IUE* observations obtained over a baseline of ~15 years indicate that the variations have been phase-locked for at least this long. In contrast to most other O stars, the UV P Cygni profile variations are not dominated by progressive DACs, but consist of absorption modulations that affect a large range of velocities nearly simultaneously. Maximum emission in Hα corresponds to minimum absorption in the C IV resonance line.

The regularity of the period, coupled with the phase relationship between Hα and the UV wind lines, can be explained qualitatively by an oblique magnetic rotator model (Stahl et al. 1996; Gagné et al. 1997). However, as with ζ Pup, some form of asymmetry in the field appears to be required to explain the single episode of modulation per rotation. Babel & Montmerle (1997; see also the contributions by Babel and Shore to this .Colloquium) have developed a detailed description of the magnetosphere of θ^1 Ori C in terms of their "magnetically confined wind shock" model, which seems to be able to reproduce the observed X-ray variability with a surface magnetic field strength of ~300 G.

However, in the context of the oblique magnetic rotator model, the 15.422-day period must be associated with the rotation period of the star. If the radius of θ^1 Ori C is similar to other O7 dwarfs, then Table 1 shows that the expected rotational period is in fact much shorter. Either the radius of this star is bigger than expected, or the photospheric lines are substantially broadened by a mechanism other than rotation. There is some evidence to support that the latter possibility since Stahl et al. (1996) found that the photospheric variations (which presumably arise from surface abundance anomalies caused by the magnetic field) are confined to a velocity range of $\pm 12\,\mathrm{km\,s^{-1}}$ centered on the systemic velocity of the star. This is much less than the measured breadth of photospheric lines (~50 $\mathrm{km\,s^{-1}}$; Table 1), which also appear to be very symmetric. The origin of the excess broadening is unknown.

Despite the discrepancy between P_{obs} and the estimated P_{rot}, there is nearly universal agreement that θ^1 Ori C is a hot analog of the chemically peculiar, magnetic Bp stars. As such, it is probably the best candidate for the detection of a magnetic field in an O-type star. Even though fields that are well below the current detection thresholds could strongly influence the emergence of its stellar wind, it is nonetheless disappointing that the magnetic field of θ^1 Ori C remains undetected (Mathys; this Colloquium).

3.3 HD 64760

HD 64760 has an extraordinarily large $v_{\mathrm{rot}} \sin i$ for its spectral type and luminosity class (Table 1), which implies that it is an intrinsically rapid rotator with an inclination close to 90°. Unfortunately, its radius can only be estimated from coarse calibrations based on spectral classification. Consequently,

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its rotational period is not known reliably: the best guess is $\sim 5 \pm 1$ days, though values outside this range are not excluded.

Prinja et al. (1995) detected periodic variations in the UV wind lines of HD 64760 in the long time series obtained during the *IUE* MEGA Campaign (Massa et al. 1995a). Fullerton et al. (1997) showed that this periodic component results from two quasi-sinusoidal fluctuations with periods of 1.202 ± 0.004 and 2.44 ± 0.04 days. The 1.2-day period has been detected weakly in UV photospheric lines (Howarth et al. 1998), while the 2.4-day period has been seen in Hα (Kaufer, private communication) and in UV data from a previous *IUE* campaign (Fullerton et al. 1997). It is not completely clear which of these periods is the more fundamental. Since they are broadly consistent with a quarter and a half of the estimated $P_{\rm rot}$, they have been attributed to rotational modulation by wind features that recur 4 times around the circumference of the star, with every second feature being different for some reason. However, as Howarth et al. (1998) discuss, this interpretation is not very secure because of the large uncertainties in $P_{\rm rot}$.

The periodic variations coexist with DACs, but do not appear to be linked to their recurrence or propagation. In contrast to DACs, the periodic component of the wind variability consists of modulations of the line flux that affect a large range of velocities at any given time, particularly in the absorption trough of a P Cygni profile. However, since the modulations can also be traced through the emission lobe, they must be caused by structures in the wind that are longitudinally extended. Within a P Cygni absorption trough, the modulations exhibit the curious property of simultaneously evolving toward larger and smaller line-of-sight velocities, a phenomenon that is known as "phase bowing". Owocki et al. (1995) showed that phase bowing can be explained quite naturally by corotating, spiral-shaped wind structures, which exit the column of absorbing material projected against the stellar disk simultaneously at two different line-of-sight velocities.

Thus, phase bowing is an important diagnostic of the geometry of the stellar wind structures responsible for the observed modulations. Fullerton et al. (1997) used this phenomenon to show that higher ions are concentrated along the inner, trailing edge of spiral-shaped perturbations in the wind of HD 64760. By using a simplified kinematic model, they inferred that the velocity law governing the radial flow of material is normal. They suggested that the periodic variations in the wind of HD 64760 are due to corotating interaction regions (CIRs), which are spiral-shaped perturbations caused by the collision of fast and slow wind streams that emerge nearly radially from different longitudinal sectors of the stellar surface; see, e.g., the contribution by Owocki to the Colloquium. Howarth et al. (1998) concluded that the 1.2-day photospheric period is due to NRP, which could serve as the source for these longitudinally-spaced fast/slow wind streams. Although there are difficulties associated with this conjecture (e.g., the pulsations may not corotate with the stellar surface), the detection of the same period in the photospheric and wind lines of HD 64760 provides strong evidence that wind structure is generated by deep-seated, photospheric processes.

4 Concluding Remarks

Until the radii of individual stars can be measured precisely, there seems to be little hope of showing definitively that the periodic component of stellar wind variability is due to rotational modulation. Nevertheless, the case studies presented here provide circumstantial evidence that such modulation does occur. However, they also caution against trying to fit all observations with one model: *none* of the case studies look very similar to each other, which implies that a variety of processes may be at work or that there are strong observational selection effects. For example, the visibility of phase bowing is expected to depend strongly on the value of $v_{\rm rot}/v_\infty$, which might explain why it is rarely detected in OB stars. Observer aspect could also play a large rôle in determining the characteristics exhibited by a given class of wind structure. These difficulties can only be addressed by enlarging the sample of stars that have been monitored extensively. Acquiring such time series data remains a formidable observational challenge.

Several theoretical challenges also need to be addressed. One such challenge is to understand the circumstances that are required to ensure that large-scale wind structures can survive the ravages of the line-driven instability (see, e.g., the contributions by Feldmeier and Owocki to this Colloquium). The effect of these structures on spectroscopic estimates of the global mass-loss rate also needs to be clarified. Although the resolution of these observational and theoretical issues will require sustained effort, it will also provide deeper insights into the physics of radiatively driven winds and the photospheres from which they flow.

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Discussion

H. Henrichs: θ^1 Ori C is problematically placed on the pre-main sequence in your HRD. Wouldn't you rather like to see a much larger value for its radius to solve the rotation problem as well?
A. Fullerton: There often seem to be problems placing early O-type dwarfs in the theoretical HRD. The fundamental parameters I have adopted for θ^1 Ori C are solely based on calibrations with spectral type and may not be entirely appropriate for such a peculiar object. It would be very interesting to try to constrain these parameters (in particular the radius) more precisely by comparison with model atmosphere calculations.

A. Moffat: Can you say that all O stars show rotationally modulated winds?
A. Fullerton: At this point, I think it would be premature to say that all O stars show rotationally modulated winds. There are a handful of well-studied cases for which the evidence of rotational modulation is strong; but even the objects I have emphasized here suggest that there might be several different "flavours" of rotational modulation, which might be caused by different photospheric processes. There may also be some strong selection effects (e.g., observer aspect, ratio of $v_{\rm rot}/v_\infty$) that determine whether rotational modulation will be observable even if structures are present. So, I'm reluctant to generalize too widely, even though the necessary ingredients – rotation, a wind, and wind structures as manifested by DACs – do seem to be universal among the O stars.

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