RevMexAA (Serie de Conferencias), **38**, 119–122 (2010)

INTERFEROMETRIC OBSERVATIONS OF RAPIDLY ROTATING STARS

G. T. van Belle[1]

RESUMEN

Desde el año 2001, los interferómetros ópticos han resuelto espacialmente las superficies no esféricamente simétricas de estrellas calientes que rotan rápido. Estas observaciones han revelado que estas estrellas tienen fotósferas de forma estirada debido a la gran aceleración centrípeta, con la característica de tener dramáticos gradientes de temperatura desde el polo hasta el ecuador debido al oscurecimiento por gravedad. Aquí se presenta una breve discusión sobre los fundamentos básicos, los resultados actuales y las perspectivas futuras.

ABSTRACT

Optical interferometers have been spatially resolving the non-spherically symmetric surfaces of rapidly rotating, hot stars since 2001. These observations have revealed these stars to have photospheres stretched out of shape due to nearly overwhelming centripetal acceleration, with characteristic, dramatic temperature gradients from pole to equator due to gravity darkening. Herein is presented a short discussion on the background of the topic, current results, and future prospects.

Key Words: stars: early-type

1. INTRODUCTION

Historically, parametrization of fundamental stellar quantities has incorporated the subtle yet far-reaching assumption of the spherical symmetry of stars. This assumption has persisted for two reasons –first, the overall success it has had in characterizing stars, and second, the degree to which observational data was not available to provide guidance otherwise. "It is a capital mistake to theorize before one has data" said Sherlock Holmes (Doyle 1887)– an observation that has not universally prevented adventurous (and highly speculative) forays into theoretical landscapes far from the observational path in astrophysics. However, the degree to which rotation has been embraced as a fundamental stellar parameter over the past century has been limited at best. With the application of modern interferometric techniques, we are beginning to directly see that the appearance, structure, and eventual evolution of hot stars is substantially altered by rotation – for some objects, extremely rapid rotation.

2. HISTORY

2.1. *Spectroscopic Underpinnings*

The very beginnings of investigations of stellar rotation can be traced to Galileo's observations of sunspots (Drake 1957). However, for application further afield to the stars, development of the tool of spectroscopy was necessary, although there is clearly evidence for consideration of the effect of rotation in the intervening years upon other astronomical observables, such as photometry (cf. the work of Bouillaud in 1667 on Mira, and later by Cassini, Fontenelle, and Miraldi as presented in Brunet 1931). Thus, some 12 generations after Galileo, the rotation effect on spectral lines was actually measured first by Schlesinger (1909, 1911) for the eclipsing binaries λ Tauri and δ Libræ, leveraging the eclipse event to see variations in apparent radial velocity, as the less luminous companion occulted varying parts of the rapidly rotating primary. This effect was formally developed by Rossiter (1924) and McLaughlin (1924) and is now commonly referred to as the 'Rossiter-McLaughlin' effect, a phenomenon now commonly observed with transiting extrasolar planets and is even a tool for probing the alignment of the orbital plan relative to the stellar rotation axis (see e.g., Winn et al. 2005).

In parallel with these efforts, it was demonstrated by von Zeipel (1924a,b) that the local surface brightness at any point on a star is proportional to the local effective gravity (under the assumption of rigid body rotation), and as such, the temperature at the poles would be greater than at the equator for a rotating star. It was Slettebak (1949) who took the implications of the 'von Zeipel effect' and deduced its further implications for line shapes of rapidly rotating, bright stars. These implications were developed in detail in Collins (1963, 1965) for continuum emission,

[1]European Southern Observatory, Karl-Schwarzschild Str. 2, 85478 Garching bei München, Germany (gerard.van.belle@eso.org).

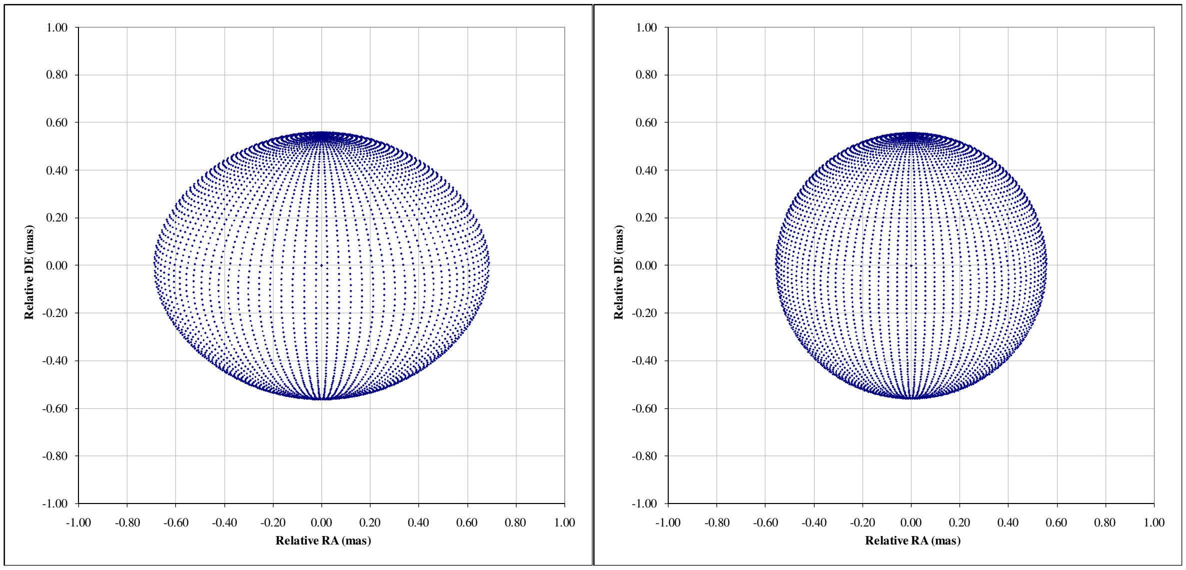

Fig. 1. Illustration of the phenomenon using a simple Roche model. Appearance is for two identical stars ($R_{\rm pole} = 3\ R_\odot$, $d = 25$ pc, $\alpha = 0°$, $i = 80°$); the star on the left is rotating with $\omega = 0.92$, while the star on the right has only $\omega = 0.001$. No contribution to pole flattening or consequences of limb and/or gravity darkening is included in this simple toy model.

and Collins & Harrington (1966), who incorporated shape distortion, aspect effects, gravity & limb darkening, and latitude variation in calculating H-β profiles. An illustration of the gross appearance effects that rapid rotation imparts upon stellar morphology is see in Figure 1.

2.2. *Interferometric Observations*

It is unclear as to when the opportunity of directly measuring stellar rotational distortion with optical interferometry[2] was first seriously considered. The advent of the first angular diameter measurement of Michelson & Pease (1921) with the 20-foot beam interferometer on the Hooker 100" was the technology gate that opened up the possibility of such measurements. However, it is clear that the expectation of potential observations did not fully develop until the spectroscopic rotational velocities were themselves surveyed between 1930 and 1960, and the implications of the extremes of those velocities evaluated, beginning in the 1960's.

Indeed, the entire field of stellar angular diameter measurements lapsed into a state of dormancy for more than 3 decades, until the innovative (and downright audacious) proposal by Hanbury Brown & Twiss (1956) to pursue this field with intensity interferometry began to produce results. These efforts led to the construction and operation of the Narrabri Intensity Interferometer (NI^2), which produced seminal results on single star diameters (Hanbury Brown et al. 1974) and binary star orbits (Herbison-Evans et al. 1971). The success of the NI^2 in this regard, combined with the maturity of the underlying theory of rapid rotators that predicted observable effects, led to early attempts to consider using NI^2 to observe the oblateness of Altair, as described in the PhD dissertations of Jordahl (1972) and Lake (1975). Unfortunately, the northern hemisphere location ($\delta = +8°52'$) of Altair is at odds with the southern location of Narrabri (latitude $= -30°19'$) and only a limited amount of observing time was available when the star was above the horizon. This in turn limited NI^2's ability to collect a sufficient range of baseline projections upon the object, and no detection of oblateness was made. The completion of NI^2 operations brought this second era of optical interferometry to a close with no detection of this phenomenon.

The third, and current, generation of optical interferometers has been where success has finally been found in probing more than just 1-dimensional characterizations of stellar sizes. Many of the facilities are characterized by multiple apertures, some even being relocatable, providing access to multiple baselines and position angles upon the sky.

Stellar oblateness was finally detected when van Belle et al. (2001) observed Altair with Palomar

[2]'Optical' interferometry is the term commonly used to refer to interferometry in the visible and near-infrared. This technology family is separate from radio interferometry in its homodyne, rather than heterodyne, nature (e.g. mix-and-detect, rather than detect-and-mix).

TABLE 1

SUMMARY OF OBSERVATIONAL RESULTS TO DATE ON RAPID ROTATORS

Star	Spectral Type	Velocity v (km s^{-1})	Inclination i (deg)	$v/v_{\rm crit}$	Orientation α (deg)	Gravity darkening β	$T_{\rm pole}$ (K)	$T_{\rm eq}$ (K)	$R_{\rm pole}$ ($R_\odot$)	$R_{\rm eq}$ ($R_\odot$)	Ref.
		$v \sin i = 210 \pm 13$, $i > 30$			-21.6 ± 6.2[b]	none applied	$< 7680 \pm 90 >$			1.8868 ± 0.0066	(1)
Altair (α Aql)	A7IV-V	273 ± 13	64	0.73 ± 0.037	123.2 ± 2.8	0.25 (fixed)	8740 ± 140	6890 ± 60	1.636 ± 0.022	1.988 ± 0.009	(2)
		285 ± 10	57.2 ± 1.9	0.923 ± 0.006	-61.8 ± 0.8	0.19 ± 0.012[c]	8450 ± 140	6860 ± 150	1.634 ± 0.011	2.029 ± 0.007	(3)
Achernar (α Eri)	B3Vpe	225[a]	>50	0.79–0.96	39 ± 1	0.25 (fixed)	20000 (fixed)	9500–14800	8.3–9.5	12.0 ± 0.4	(4)
Vega (α Lyr)	A0V	270 ± 15	4.7 ± 0.3	0.91 ± 0.03	not cited	0.25 (fixed)	10500 ± 100	8250^{+415}_{-315}	2.26 ± 0.07	2.78 ± 0.02	(5)
		274 ± 14	4.54 ± 0.33	0.926 ± 0.021	8.6 ± 2.7	0.25 (?, fixed)	9988 ± 61	7557 ± 261	2.306 ± 0.031	2.873 ± 0.026	(6)
Regulus (α Leo)	B8IVn	317 ± 3	90^{+0}_{-15}	0.86 ± 0.03	85.5 ± 2.8	0.25 ± 0.11	15400 ± 1000	10300 ± 1000	3.14 ± 0.06	4.16 ± 0.08	(7)
Rasalhague (α Oph)	A5IV	237	87.70 ± 0.43	0.885 ± 0.011	-53.88 ± 1.23	0.25 (fixed)	9300 ± 150	7460 ± 100	2.390 ± 0.014	2.871 ± 0.020	(8)
Alderamin (α Cep)	A7IV-V	283 ± 19	$88.2^{+1.8}_{-13.3}$	$0.8287^{+0.0482}_{-0.0232}$	3 ± 10	$0.084^{+0.026}_{-0.049}$	8440^{+430}_{-700}	"~ 7600"	2.175 ± 0.046	2.82 ± 0.10	(9)
		225	55.70 ± 6.23	0.941 ± 0.020	-178.84 ± 4.28	0.216 ± 0.021[c]	8588 ± 300	6574 ± 200	2.162 ± 0.036	2.74 ± 0.044	(8)

[a]Fixed from Slettebak (1982).
[b]In error, reflecting $\{u, v\}$ coordinates swap.
[c]Second solution with $\beta = 0.25$ (fixed) also presented in manuscript.
References: (1) van Belle et al. (2001); (2) Peterson et al. (2006a); (3) Monnier et al. (2007); (4) Domiciano de Souza et al. (2003); (5) Aufdenberg et al. (2006); (6) Peterson et al. (2006b); (7) McAlister et al. (2005); (8) Zhao et al. (2009); (9) van Belle et al. (2006).

Testbed Interferometer (PTI) on two baselines, leading to disparate uniform-disk size measurements, particularly in comparison to the two sizes on the check star Vega, which did agree. Application of a multi-parameter Monte Carlo solution, patterned after the similar technique applied to Keplerian orbit solutions for interferometric data (Boden et al. 1999), indicated a $v \sin i = 210 \pm 13$ km s^{-1}, in agreement with spectroscopic values. The data was insufficient to further constrain the inclination i or characterize gravity darkening, but a new sub-field in optical interferometry had been opened up by this study.

Subsequent observations of rapidly rotating stars have been carried out with the more capable facilities VLTI, NPOI, the CHARA Array. These ensuing data sets have been sufficiently rich to allow for full parameterizations of the observed objects, including constraints on inclination and gravity darkening. There have been, to date, six objects studied in-depth, which are summarized in Table 1. The typical solution set from these investigations have provided direct, observational constraints on:

- 3D orientation – both on-sky orientation of rotational axis and inclination of that axis to observer line-of-sight
- Stellar radius – both equatorial and polar
- Absolute rotational velocity
- Effective temperature and gravity darkening – as a function of latitude, leading to the concept of 'local' $T_{\rm eff}$

The astrophysical implications of this level of detail in characterizing individual stellar objects are considerable. For example, observations of Vega by Aufdenberg et al. (2006) led the investigators to substantially refine (some might say, revise) the nature and absolute amount of bolometric flux being produced by this star. Given Vega's historic role as a spectrophotometric standard object, these results potentially have far-reaching implications. In the case of Regulus, it was noted in the press release associated with the paper (McAlister et al. 2005, but interestingly enough, not in the paper itself) that the orientation of the axis of rotation was aligned with the direction of the star's proper motion. Such an observation –impossible before the CHARA Array investigation– has at least passing implications for considering the star formation environment and dynamic history of Regulus. Determinations of gravity darkening for these objects has the potential to revise the perspectives held on the radiative versus convective natures of the outer atmospheres of these hot stars, particularly in light of how some of these

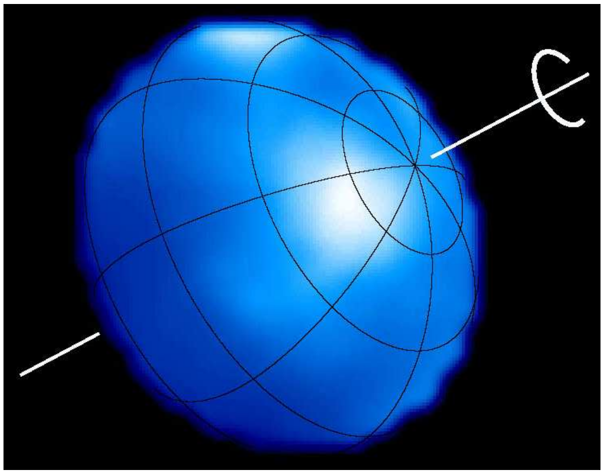

Fig. 2. Image of Altair presented in Monnier et al. (2007), overlaid with latitude/longitude grid and axis of rotation, consistent with appearance upon sky, including orientation (N is up, E is left) and gravity darkening leading to a hot, bright 'spot' at the high latitudes.

objects bridge the gap between being 'hot' and 'cool' with temperatures that vary greatly from their poles to their equators.

3. THE FUTURE OF OBSERVATIONS OF RAPID ROTATORS

As noted in the catalog suggested by van Belle et al. (2004), there are literally dozens of objects for which this sort of in-depth analysis is possible with currently available facilities, such as VLTI or CHARA, or those under construction, such as MROI. One limiting factor up until recently has been substantial observing time investment required per star to collect a sufficiently rich dataset necessary for the multi-parametric characterization task. However, with the advent of multi-baseline beam combiners, such as MIRC, AMBER, and PIONIER –and their substantially richer data cubes– this hurdle appears to be subsiding markedly: already the MIRC team has published multiple objects in short order (Monnier et al. 2007; Zhao et al. 2009) with more on the way (see Figure 2).

Additionally, these combiners allow not just for better, quicker collection of the observational data, they extend this line of investigation in two important ways. First, the increase in quantity and type of data allow for simple imaging of the objects, rather than just model-fitting. Second, the speed with which the data cubes can be collected open the door for examination of time-variable phenomena — for example, if there are any subtle surface features such as spots that rotate in and out of view.

My expectation is that this area of research will continue to mature and develop. Within the next 5 to 10 years it would not be unreasonable to see a moderate-scale survey of this nature, covering one or two dozen objects in a uniform study at one of the newer facilities. Additionally, long-term monitoring s of a smaller number of objects will also take place for the brighter prototypes. An aesthetically pleasing by-product of such investigations will be "family portraits" of our immediate neighbors; the more practical result will be unparalleled insights into the structure and evolution of these stars.

REFERENCES

Aufdenberg, J. P., et al. 2006, ApJ, 645, 664
Boden, A. F., et al. 1999, ApJ, 515, 356
Brunet, P. 1931, L'introduction des théories de Newton en France au XVIII ème siècle (Paris: A. Blanchard)
Collins, II, G. W. 1963, ApJ, 138, 1134
_________. 1965, ApJ, 142, 265
Collins, II, G. W., & Harrington, J. P. 1966, ApJ, 146, 152
Domiciano de Souza, A., et al. 2003, A&A, 407, L47
Doyle, A. C. 1887, Beeton's Christmas Annual, 28, 1
Drake, S. 1957, Discoveries and Opinions of Galileo (Garden City: Doubleday Anchor)
Hanbury Brown, R., Davis, J., & Allen, L. R. 1974, MNRAS, 167, 121
Hanbury Brown, R., & Twiss, R. Q. 1956, Nature, 178, 1046
Herbison-Evans, D., Hanbury Brown, R., Davis, J., & Allen, L. R. 1971, MNRAS, 151, 161
Jordahl, P. R. 1972, PhD thesis, The University of Texas at Austin, USA
Lake, R. J. W. 1975, PhD thesis, University of Sydney, Australia
McAlister, H. A., et al. 2005, ApJ, 628, 439
McLaughlin, D. B. 1924, ApJ, 60, 22
Michelson, A. A., & Pease, F. G. 1921, ApJ, 53, 249
Monnier, J. D., et al. 2007, Science, 317, 342
Peterson, D. M., et al. 2006a, ApJ, 636, 1087
Peterson, D. M., et al. 2006b, Nature, 440, 896
Rossiter, R. A. 1924, ApJ, 60, 15
Schlesinger, F. 1909, Publ. Allegheny Obs., 1, 134
_________. 1911, MNRAS, 71, 719
Slettebak, A. 1949, ApJ, 110, 498
_________. 1982, ApJS, 50, 55
van Belle, G. T., et al. 2006, ApJ, 637, 494
van Belle, G. T., Ciardi, D. R., Thompson, R. R., & Akeson, R. L. 2004, in IAU Symp. 215, Stellar Rotation, ed. A. Maeder & P. Eenens (San Francisco: ASP), 177
van Belle, G. T., Ciardi, D. R., Thompson, R. R., Akeson, R. L., & Lada, E. A. 2001, ApJ, 559, 1155
von Zeipel, H. 1924a, MNRAS, 84, 665
_________. 1924b, MNRAS, 84, 684
Winn, J. N., 2005, ApJ, 631, 1215
Zhao, M., et al. 2009, ApJ, 701, 209