Astrophysical Applications of Stellar Pulsation
ASP Conference Series, Vol. 83, 1995
R. S. Stobie and P. A. Whitelock, eds.

Interferometry of Cool Pulsating Stars

Chris Haniff
Mullard Radio Astronomy Observatory, University of Cambridge, Cavendish Laboratory, Madingley Road, Cambridge, CB3 OHE, England

Abstract. The drive for high-angular resolution from the ground has led to the development of optical and near infrared interferometric telescopes analogous to radio synthesis arrays. These now provide a diffraction-limited imaging capability well suited to studies of nearby cool giants and supergiants. In this review I summarise the current status of these instruments, their scientific potential for studies of cool pulsating variables (LPVs), and present some recent results that highlight the promise that such methods hold.

1. Introduction

The application of interferometric techniques to astronomical imaging has had a long and successful history, and is exemplified most visibly nowadays in large radio synthesis telescopes such as the VLA & AT. Recently such methods have been transferred to optical and near-infrared (NIR) wavelengths and are reaching fruition in a new generation of separated-element interferometric telescopes. Because of their similarity in implementation, throughout this review any mention of optical interferometry should in fact be taken to refer to both optical and NIR systems. The purpose of this review is in essence threefold. First, to explain why and how interferometric methods have only now expanded into the optical and NIR wavebands. Second, to outline the specific astrophysical questions related to LPVs that can be addressed by such instruments. And finally, to demonstrate, by way of examples, the contribution that imaging interferometry is already making to our understanding of cool pulsating variables today.

2. Michelson interferometry in the 1990s

Before discussing the scope of interferometry it is worthwhile stepping back and reviewing exactly what we mean when we talk of an "interferometer". My own feeling is that most optical astronomers, have a reasonably well defined, though outdated, picture of an unwieldy instrument attached to the front of a large telescope, producing an image crossed by fringes, i.e. they envision a classical Michelson stellar interferometer. Only infrequently do they recognise optical interferometers as precise analogues of radio synthesis arrays, where the primary observable of the instrument is not an image at all, but a measurement of the spatial coherence function of the radiation from the source. Hereafter, I shall use the terms spatial coherence function and visibility function interchangeably.

For the sake of completeness, I remind the reader that the visibility function and source brightness distribution are related to each other, in most cases of interest, via a Fourier transform.

In fact it is instructive to use a typical radio synthesis telescope to characterise the features we ought to expect in its optical counterpart:

- Small unit telescopes: these should be smaller than the characteristic scale size of the atmospheric wavefront perturbations, r_o. At cm radio wavelengths this is typically many hundreds of metres, and so is often not an important design constraint. However, for optical and NIR observations this restriction implies that $D < 0.1\mathrm{m} - 1.0\mathrm{m}$.
- Long baselines: $B \gg D$. Usually this applies to all the interferometer baselines, with even the shortest spacings being many times the unit telescope size. This implies a lack of sensitivity to large-scale structures on the sky.
- Short exposure times: $T_{exp} <$ the timescale associated with the atmospheric wavefront perturbations, τ_o. This scale is much longer at radio wavelengths than in the optical/NIR regime, where typical exposure times lie in the range 0.01s – 0.1s. In general $T_{exp} \ll$ the total time to observe the source.
- The primary observable is the spatial coherence function or complex visibility function, not an image as is the case for a conventional telescope. In this sense the two processes of data acquisition and image recovery can be treated as quite separate steps, with the production of an image being one of many possible procedures for visualising the interferometer's output.

Given the above, we should expect interferometers to have good spatial resolution, but very poor sensitivity, at least when compared to filled-aperture telescopes. At optical and NIR wavelengths the small values of r_o and τ_o limit the scope of interferometry to bright astrophysical targets, but the ability to overcome the seeing limit means that interferometer arrays are ideally suited for studying luminous evolved giants and supergiants whose apparent angular sizes are well matched to the resolutions attainable with 10 – 100m baselines.

2.1. Developments in optical interferometry

Perhaps the most important recent advances in interferometry have been the development of methods to recover the phase of the visibility function from atmospherically perturbed measurements. In the absence of phase information, unambiguous image reconstruction is usually not possible, and so for many years interferometric methods played only a minor role in optical and NIR astronomy.

Current techniques take advantage of the fact that, while individual measurements of the visibility phase are corrupted by atmospheric turbulence, certain combinations of them are immune to this type of disturbance. More specifically, sums of Fourier phases measured round closed loops of baselines, or equivalently the arguments of the products of the complex visibilities on these baselines, remain good observables. These so-called closure, or bispectral, phases provide access to the true source visibility phases, albeit in the form of linear combinations, and thereby lead to the following important repercussions:

- Imaging becomes feasible: although for a 3-element interferometer (the minimum sized array that permits the use of closure techniques) the fraction of visibility phase information recoverable is relatively small, for arrays with larger numbers of telescopes high-fidelity imaging of complex sources is possible. The use of these closure methods has been the key to the success of radio VLBI (see, e.g., Pearson & Readhead 1984).
- Information on scales smaller than the Rayleigh limit ($\theta_{min} \sim \lambda/B_{max}$) becomes accessible. This does not contradict the usual criterion for resolving power, but reflects the fact that closure phases are sensitive diagnostics for certain source structures. In particular, symmetric components in the source produce no closure phase signal, whereas asymmetric structures can be reliably detected even when present on scales smaller than θ_{min}.

Verification of these two new possibilities for optical interferometry had to wait until the late 1980s, and so the status of optical interferometry is comparable to that of radio synthesis in its early days. Nevertheless, the demonstrable success of interferometric imaging experiments and the, perhaps unexpected, robustness of the closure phase to calibration errors, has meant that spatial interferometry is a far more powerful tool nowadays than it has ever been.

2.2. Current interferometer projects

The scientific potential of interferometric imaging can best be gauged by the large investment of both effort and money in the field today. Table 1 provides a brief summary of optical interferometers currently operational, or in the process of construction or planning. Only systems designed for closure-phase imaging are listed, and so a number of scientifically important 2-element instruments, including GI2T and SUSI, are missing. Of those listed, COAST, ISI and IOTA are operational, though the last two of these are still awaiting their third unit telescopes. Further details of all of these interferometers can be found in Breckinridge (1994).

Name	Location	Type	Operating Bandpass
NPOI	Anderson Mesa, AZ	Imaging/Astrometry	Optical
COAST	Cambridge, UK	Imaging	Optical/Near IR
CHARA	t.b.d.	Imaging	Optical/Near IR
ISI	Mt. Wilson, CA	Imaging	Mid IR
IOTA	Mt. Hopkins, AZ	Imaging	Near IR
VLTI	Paranal, Chile	Imaging	Optical/Near IR
KECK	Mauna Kea, Hawaii	Imaging/Astrometry	Near/Mid IR

Although these interferometers differ greatly in scope and scale, not surprisingly they share numerous common features:

- Small telescopes in the range 10cm to 2m. Apart from the KECK and VLTI arrays, which will utilise the very large unit telescopes in combination with arrays of smaller outrigger telescopes, most of these interferometers have been designed to operate with aperture sizes of $\sim r_o$.
- Baselines in the range tens to hundreds of metres. This implies resolving powers of between one and four milliarcseconds, sufficient to permit imaging of LPVs out to ~ 1kpc.
- Broad band imaging capabilities, with spectral resolutions from 10 to 1000. Most of these interferometers have use medium and narrow-band filters to define the bandpasses observed. However, given the diagnostic importance of spectral information, beam combination architectures incorporating dispersion are envisioned in all second-generation detector subsystems.

Apart from separated-element arrays, individual monolithic telescopes can also be operated in an interferometric mode. This is accomplished by apodizing the telescope pupil with a mask perforated with a number of appropriately arranged holes, thereby emulating a Fizeau interferometer (see, e.g., Haniff et al. 1987). When implemented on 10m-class telescopes this type of approach can be very attractive for studies of nearby LPVs for which resolutions of the order of ten milliarcseconds are still scientifically valuable.

3. Science goals for cool pulsating stars

Despite much observational work, numerous aspects of the theory and physics of Mira variables still remain in dispute. To some extent this is a consequence of their intrinsic complexity, but the paucity of precise observational diagnostics has been a significant impediment to progress. Interferometry offers the potential for addressing a number of pressing issues, some of which are outlined below:

3.1. Photospheric angular diameters

Ostensibly one of the most straightforward applications of interferometry is to establish reliable angular sizes for M-type variables and hence determine the effective temperature scale for these stars. This has been hampered in the past by the wealth of atomic and molecular features present in the optical spectra of Miras. These make it difficult to isolate bandpasses that are sensitive only to photospheric emission, and are responsible for a strong wavelength dependence of apparent angular size.

One of the most suitable regions of the spectrum for this type of work lies between 1 and 2μm (Bessell et al. 1989). However, until recently, most studies have had to rely upon occultation techniques to provide the necessary resolution to achieve accurate results at these longer wavelengths (see Richichi 1994 for a review of these methods). Interferometry now seems well placed to become the method of choice for stellar diameter measurement, offering full sky coverage, high resolution, and of course freedom from the temporal constraints set by the lunar motion. Furthermore, the combination of adaptive optics and interferometry on large monolithic telescopes offers the prospect of measurements shortwards of 0.4μm where alternative bandpasses exist that also probe the deeper continuum layers of the atmosphere (Bessell et al. 1989).

3.2. Pulsation modes of Mira variables

The mode of pulsation of Miras has remained controversial for many years, with photometric studies suggesting overtone pulsation, but shock models implicating fundamental mode pulsation in order to reproduce the velocities seen in high-resolution NIR spectra (see Wood, these proceedings, for a discussion of these issues). In principle, selection between these two options ought to be simple, requiring estimates only of the period, P, mass, M, and radius, R, of the star. The combination of these three quantities in the pulsation constant, $Q = P(M/M_\odot)^{1/2}(R/R_\odot)^{-3/2}$, would then provide the necessary discriminant. On the assumption of a consensus as to the values of Q expected for fundamental and first overtone pulsation, it seems likely that the availability of a small number of precise interferometric diameter estimates at selected photospheric bandpasses, together with accurate parallax distances, either from HIPPARCOS or modern ground-based measurements (Gatewood 1992), will soon put an end to this impasse.

3.3. Testing models of Mira atmospheres

Over the past decade, theoretical modelling of LPV atmospheres has matured greatly. Not content with static plane-parallel models, workers have introduced increasing levels of sophistication in order to better accommodate, for example, the sources of opacity in the cool outer layers of Miras as well as the stratification expected in a periodically perturbed atmosphere (Scholz & Takeda 1987; Bessell et al. 1989; Bessell et al. 1995). With interferometry it has now become possible to check these models directly.

Apart from verifying the predicted variations of apparent diameter with λ, and locating the regions responsible for the emission lines seen at certain phases of the variability cycle, one of the most interesting possibilities will be to monitor the temporal behaviour of the atmospheric structure. This will require only moderate resolution but high sensitivity and fidelity, particularly if subtle variations are to be detected. Typical of these are the relatively small modulations predicted for the photospheric diameter, which have been estimated to lie in the range 5 – 10% on the basis of bolometric photometry (Tuthill et al. 1994). Dynamical models of Miras (see Wood, these proceedings) often suggest larger amplitudes (30–50% for fundamental models) and so it ought to be straightforward to confirm these predictions with interferometric monitoring.

3.4. Surface imaging of Mira variables

The most exciting and challenging role for interferometry will be to reveal the surface morphologies of LPVs directly. Indirect evidence for deviations from circular symmetry and an otherwise uniform brightness distribution has often been cited on the basis of polarimetric studies (Shawl 1974; Boyle et al. 1986) and observations of non-uniform distributions of SiO masers (e.g., Diamond et al. 1994; Greenhill et al. 1995), which trace material close to the stellar surface. Asymmetries on larger scales have also been detected using molecular species

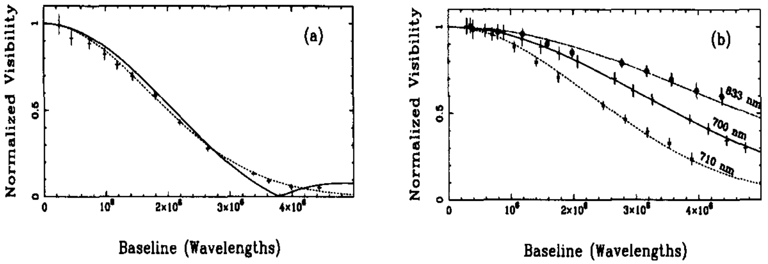

Figure 1. Measured visibility data for W Hya (a) and R Cas (b). In the first panel the data are plotted together with two models: the filled line is a theoretical prediction, while the dotted line is a Gaussian fit. The data for R Cas are typical for Miras, which show large changes in apparent diameter as a function of wavelength.

such as CO (Planesas et al. 1990), and it remains to be seen to what extent these are governed by corresponding asymmetries at the stellar surface.

High quality imaging will demand good Fourier plane coverage and both accuracy and precision in the visibility measurements. Observations within the optical bandpass will be best suited to identify and define the number, location and timescales of any surface phenomena, while those at longer wavelengths will begin to probe hot dust close to the photosphere. Sequences of images should uncover, not only the location of the hottest dust, but also identify when in the pulsation cycle it forms and hence whether or not mass loss in Miras is sporadic or more closely linked to the regular pulsation cycle.

4. Results from ground-based programmes

Though I have talked thus far about the future role of interferometry, its notable successes to date deserve some mention. Rather than providing an exhaustive review of all previous studies, for reasons of expediency I have concentrated on an admittedly biased, but hopefully representative, selection of results from our group in Cambridge. These were obtained by a number of my colleagues during interferometric observing campaigns that utilised the 4.2 WHT telescope in La Palma between 1991 and 1994 : I am very grateful to them for allowing me to present their results here.

4.1. Atmospheric structure

Measurements of visibility amplitude as a function of baseline have now become almost routine (see, e.g., Benson et al. 1991; Quirrenbach et al. 1993), although in most instances the range of baselines used is small, which can limit the scope of any interpretation. Recently, workers have begun to use more extensive datasets to search for deviations from uniform limb-darkening and circular symmetry. Figure 1a shows data for W Hya obtained at 700nm in July 1992. The measurements appear to fit a smooth Gaussian profile in preference to a

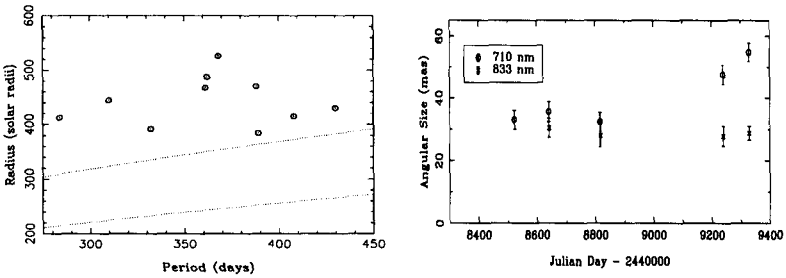

Figure 2. The left hand panel shows photospheric radii for a sample of nearby Miras from Haniff et al. (1995). The dotted lines are predictions for $1M_{\odot}$ (lower) and $1.5M_{\odot}$ (higher) fundamental mode pulsators. The other panel shows the measured size variations of *o* Ceti between 1991 and 1993. Note the rapid increase in size towards the end of this period, and its prominence in the 710nm (TiO) bandpass.

theoretical limb-darkened model. This appears to be a general trend for the sample of LPVs we have observed, with the visibility amplitudes at the longer baselines not showing any pronounced nulls, indicative of very smooth brightness profiles.

The λ-dependence of the apparent diameters of LPVs was first noticed by Labeyrie and his colleagues in the late 1970s (Labeyrie et al. 1977; Bonneau et al. 1982). Nowadays observations are targeted towards selected narrow bandpasses over as wide a range of λ as possible so as to permit useful comparisons with models. Figure 1b shows data for the source R Cas: the sequence of wavelengths 833 → 700 → 710nm corresponds to layers increasingly distant from the centre of the star, and highlights the strength of the wavelength dependence.

As mentioned by Wood (these proceedings) model atmospheres can be used to derive correction factors relating these quasi-monochromatic measurements to the true photospheric size. Tuthill and colleagues (Tuthill et al. 1994; Haniff et al. 1995) have used such models, together with interferometric data and distances based on the (K, log P) relation, to estimate the linear radii for a sample of 10 nearby Miras. Their results are summarised in Figure 2a. Subject to the usual caveats regarding the correction factors used, their data appear to rule out fundamental mode pulsation for this sample of short period ($P \leq 450$days) LPVs. Hopefully, interferometric measurements in less confused regions of the spectrum will soon place this result on a sounder footing.

4.2. Variability effects

There has been relatively little interferometric monitoring of the spatial structure of Mira variables. Variations in the shape of Mira itself were first noticed by Karovska et al. (1991) using speckle interferometry, and further studied by Quirrenbach et al. (1992) with the MkIII optical interferometer. Their data showed variability on a timescale of less than a month, but its interpretation was made difficulty by the broad (22nm) bandpass of their instrument. Some of our own results for Mira are shown in Figure 2b. Measurements in pseudo-

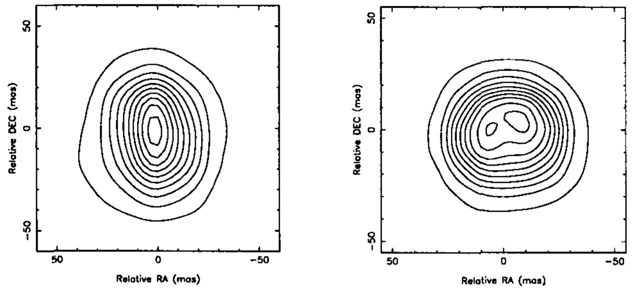

Figure 3. Aperture synthesis images of R Cas (left) and α Ori (right). The data were secured at 710nm and 700nm respectively. North is up and East to the left. Contour levels are from 5 to 95% of the peak flux, in increments of 10%.

continuum bandpasses exhibit relatively small fluctuations, but at wavelengths affected by TiO absorption the apparent size of the star can vary considerably over quite short timescales. More work certainly remains to be done, both in terms of monitoring the smaller modulation of the photospheric radius, as well as identifying any links these larger fluctuations may have with mass-loss and dust formation.

4.3. Stellar surface imaging

Probably the most unusual results from spatial interferometry have arisen from imaging experiments (see, e.g., Buscher et al. 1990; Wilson et al. 1992). These have uncovered several especially intriguing phenomena:

- Gross deviations from circular symmetry: these are clearly demonstrated in Figure 3a which shows the nearby LPV R Cas. The highly distorted atmosphere showed little change between July 1992 and September 1993, and is the most extreme example of its type we have observed. The connections, if any, of this puzzling morphology with the pulsation cycle, with deeper surface asymmetries (see below) or with possible stellar rotation all remain to be determined.

- Isolated unresolved hotspots of emission on the stellar surface: although not obvious from the presentation of Figure 3a, for a sample of 10 nearby Miras including R Cas, we have found no cases where a star has exhibited a distortion from circular symmetry that is symmetric. The key to this discovery has been the availability of closure phase information as a diagnostic for asymmetric structure. A clearer demonstration of this type of surface phenomenon is presented in Figure 3b, which shows a map of the M supergiant α Ori. The two hotspots contain 12% and 6% of the total flux respectively, and appear to show little variation in brightness with λ. For the LPV sample, the hotspots detected have similar fluxes, while for other supergiants we have studied they can sometimes be a factor of two brighter.

The ubiquity of these types of surface and atmospheric disturbances is quite remarkable: observations at different epochs and wavelengths have consistently revealed them for almost every M giant and supergiant we have studied with sufficient resolution. One possibility is that we are seeing the effects of large scale convective zones on the stellar surface (Schwarzschild 1975). The number, size, and luminosity of the hotspots are certainly consistent with such an hypothesis, and could go some way towards explaining the low-amplitude chaotic fluctuations seen in the light curves of many of these sources.

5. Conclusions

Interferometric imaging is already providing a unique tool for cool variable star research today, and the advent of long-baseline interferometers looks set to reveal a range of unsuspected phenomena. Two areas appear particularly fruitful. Observations in the infrared, targeted towards the interface between the stellar surface and circumstellar environment, will help to understand the geometry and dynamics of mass loss, as well as the link between mass loss and pulsation, and will call for long-baseline instruments. At the other extreme, the combination of adaptive optics and interferometry on 10m-class telescopes offers the possibility of very narrow-band ($R \sim 1000$) diffraction-limited imaging of nearby LPVs, isolating individual atmospheric layers and monitoring their evolution in time.

Acknowledgments. It is a pleasure to thank the members of our group in Cambridge involved in our aperture synthesis programme, in particular John Baldwin & Peter Tuthill, and also Michael Feast & Michael Scholz for their useful input. I am very grateful to the Royal Society for their financial support.

References

Benson, J.A., Dyck, H.M., Ridgway, S.T., Dixon, D.J., Mason, W.L., & Howell, R.R. 1991, AJ, 102, 2091

Bessell, M.S., Brett, J.M., Scholz, M., & Wood P.R. 1989, A&A, 213, 209

Bessell, M.S., Scholz M., & Wood P.R. 1995, A&A, Submitted

Bonneau, D., Foy, R., Blazit, A., Labeyrie, A. 1982, A&A, 106, 235

Boyle, R.P., Aspin, C., Coyne, G.V., & McLean, I.S. 1986, A&A, 164, 310

Breckinridge, J.B. 1994, Proc SPIE, 2200

Buscher, D.F., Haniff, C.A ., Baldwin, J.E., & Warner, P.J. 1990, MNRAS, 245, 7p

Diamond, P.J., Kemball, A.J., Junor, W., Zensus, A., Benson, J., & Dhawan, V. 1994, ApJ, 430, L61

Gatewood, G. 1992, PASP, 104, 23

Greenhill, L.J., Colomer, F., Moran, J.M., Backer, D., Danchi, W.C., & Bester, M. 1995, ApJ, submitted

Haniff, C.A., Mackay, C.D., Titterington, D.J., Sivia, D., Baldwin, J.E., & Warner, P.J. 1987, Nature, 328, 694

Haniff, C.A., Scholz, M., & Tuthill, P.G. 1995, MNRAS, In press

Karovska, M., Nisenson, P., & Papaliolios, C. 1991, ApJ, 374, L51

Labeyrie, A., Koechlin, L., Bonneau, D., Blazit, A., & Foy, R. 1977, ApJ, 218, L75

Pearson, T.J. & Readhead, A.C.S. 1984, ARA&A, 22, 97

Planesas, P., Kenney, J.P.D., & Bachiller, R. 1990, ApJ, 364, L9

Quirrenbach, A., Mozurkewich, D., Armstrong, J.T., Johnston, K.J., Colavita, M.M., & Shao, M. 1992, A&A, 259, L19

Quirrenbach, A., Mozurkewich, D., Armstrong, J.T., Buscher, D.F., & Hummel, C.A. 1993, ApJ, 406, 215

Richichi, A. 1994, in Very High Angular Resolution Imaging, J.G.Robertson & W.J.Tango, Kluwer: Dordrecht, 71

Scholz, M., & Takeda, Y. 1987, A&A, 186, 200 (erratum: A&A, 196, 342)

Schwarzschild, M. 1975, ApJ, 195, 137

Shawl, S.J. 1974, PASP, 86, 843

Tuthill, P.G., Haniff, C.A., Baldwin, J.E., & Feast, M.W. 1994, MNRAS, 266, 745

Wilson, R.W., Baldwin, J.E, Buscher, D.F., & Warner, P.J. 1992, MNRAS, 257, 369

Discussion

Chapman: Are you confident that your visibilities at the highest spatial frequencies are not affected by instrumental effects, i.e. could instrumental effects explain the offsets between the data and limb-darkened models?

Haniff: Yes we are. Our calibration procedures are quite extensive, and at the longest baselines the visibilities stay so high that it's difficult to see how large enough errors can have arisen to erase the nulls in the visibility function.

Kawaler: Have you looked at any unresolvable stars intentionally and, if so, what do these sources look like?

Haniff: Yes, a standard part of our procedure is to observe stars known to have small apparent diameters (e.g., early type stars) so as to calibrate our optical system. For these we see reductions in visibility consistent with atmospheric decorrelation, and closure phases close to zero, as expected for unresolved targets.

Hughes: Are the positions and changes in positions of the hotspots consistent with planetary orbits?

Haniff: Thus far we have been unable to monitor the change in position of any individual feature: what we see are either different features at different epochs, or the vanishing of a single feature between observations several months apart. Given these limitations, there does not appear to be any evidence yet of a systematic variation in the hotspot parameters that one could associate with planetary motion.

Smith: Your resolved features in α Ori may be related to the "long periods" discovered in this and other M supergiants and giants on the basis of their lightcurves. Over the last decade we (Smith et al. these proceedings) have found that both the H-α and CaII fluxes are correlated with these long periods. Our belief is that these periods could arise from an analogue to supergranulation in this and related stars.

Haniff: That's an interesting point. With our current poor temporal sampling we have not yet been able to determine any long term trends in the features detected on the stellar disk. However it would certainly be interesting to see if we could correlate our images with your data at the relevant epochs.