Mira science with interferometry: a review

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ABSTRACT

Model-predicted and observed properties of the brightness distribution on M-type Mira disks are discussed. Fundamental issues of limb-darkening and diameter definition, of assigning observational data to diameter-type quantities and of interpreting such quantities in terms of model diameters are outlined. The influence of model properties upon interpretation of measured data is clarified. The dependence of the centre-to-limb variation (CLV) of intensity on wavelength, on stellar parameters and on variability phase and cycle may be used for analyzing the geometrical and physical structure of the Mira atmosphere, for determining fundamental stellar parameters, and for investigating the quality of models. Desirable future observations include simultaneous observations in different spectral features at different phases and cycles, observation of the position of the shock front and observation of the time- and wavelength-dependence of deviations from spherical symmetry.

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1. INTRODUCTION

Mira science with interferometry began 7 decades ago when Pease (1931) reported for o Cet a diameter of 47mas measured with Michelson’s interferometer at Mount Wilson Observatory. A critical assessment of this result was not published, but some aspects were discussed 37 years later in Hanbury Brown’s (1968) review of stellar diameter measurements. The next step towards studying Mira variables by means of interferometry was done in a series of pioneer observations by Labeyrie and co-workers who measured diameters of o Cet and R Leo with the speckle interferometry technique (Bonneau & Labeyrie 1973; Blazit et al. 1977; Labeyrie et al. 1977; Bonneau et al. 1982). From these speckle observations, it became evident that diameters measured in different bandpasses of the 0.40 to 1.04\,\mu m region are so strongly wavelength-dependent that the stellar atmosphere must be geometrically extended and strong-TiO molecular bands are formed at substantially larger distances r from the star’s center than near-continuum spectral features. At about the same time, the first high-precision measurements of M-type Mira diameters obtained at Kitt Peak National Observatory with the lunar-occultation technique (U Ori: Ridgway et al. 1977; S Psc, U Ari, VV Sgr: Ridgway et al. 1979; S Vir: Ridgway et al. 1980) became available.

The question whether measured differences between monochromatic diameters reflect real differences between positions of photon-emitting layers or are noticeably affected by differences of the shape of the centre-to-limb variation (CLV) of intensity was addressed in the model studies of Scholz & Takeda (1987) and Bessell et al. (1989). These authors demonstrated (i) that Mira atmospheres are, indeed, geometrically very extended (and must not be computed in the compact approximation) if dynamic effects taken into account; and (ii) that the wavelength-dependence of the CLV shape may be strong and has to be accounted for in converting measured visibility fit diameters into meaningful geometric diameters. Baschek et al. (1991) investigated the meaning of various radius-type quantities in case of an extended atmospheric configuration. Among these, the intensity...
radius is defined in terms of the CLV shape which, in principle, is an observable quantity, whereas the optical-depth radius is defined as the distance of the $\tau=1$ layer ($\tau = \text{radial optical depth}$) from the star’s centre, which is the usual radius definition in modelling work but no observable quantity.

In the past decade, high-precision interferometric observations and advanced models of M-type Mira variables have become available which allow to determine physically meaningful diameters and, moreover, may be used for analysis of the atmospheric structure and for testing the quality of Mira models. The following topics will be discussed in this contribution: (a) typical properties of monochromatic CLVs; (b) basic problems of defining and measuring monochromatic radii; (c) concepts of determining “the radius” of a Mira variable to be adopted, e.g., for describing stellar evolution and pulsation; (d) monochromatic interferometric observations as a tool for analyzing the geometrical and physical structure of the Mira atmospheres and for scrutinizing modelling assumptions; (e) prospects of Mira interferometry including observations of shock front positions, of deviations from spherical symmetry, and of effects generated by atmospheric dust in the transition zone from atmospheric to circumstellar material.

The wide field of physics and interferometric observations of circumstellar matter and their interpretation will not be reviewed here. Also, this contribution does not cover C-type Miras because neither observational nor theoretical studies of CLV properties and radius interpretation are so far available.

2. MONOCHROMATIC BRIGHTNESS DISTRIBUTION

Whilst the brightness distribution on compact-atmosphere disks can in most cases be satisfactorily described in terms of simple CLV approximations (see, e.g., Hestroffer 1997; Scholz 1997), among these the uniform disk (UD) and the fully darkened disk (FDD), such approximations often fail for Mira variables. CLV reconstructions from lunar occultation data were attempted for 4 M-type Miras (Bogdanov & Cherepashchuk 1991; Di Giacomo et al. 1991) which, despite rather limited accuracy, indicate unusual brightness profiles. CLV reconstructions from interferometric data are so far not available, but evidence for strong deviations from conventional moderate limb-darkening was presented by several authors who reported visibilities corresponding to a Gaussian-like brightness distribution (e.g. Wilson et al. 1992; Haniff et al. 1995; Tuthill et al. 1995; Hofmann et al. 2000, 2001; Young et al. 2000 (S-type Mira χ Cyg)). Perrin et al. (1999) also measured in R Leo a K bandpass visibility that seems to indicate a Gaussian-like CLV shape.

The simple exploratory M-type Mira model atmospheres of Bessell et al. (1989) predict a large variety of CLV shapes (Scholz & Takeda 1987), ranging from nearly uniform and moderately darkened disks to complex CLVs with, e.g., a Gaussian-like or a two-component appearance including sometimes small limb-brightening. More advanced dynamic models and resulting visibilities in selected near-continuum to strong-absorption bandpasses confirm this diversity (Bessell et al. 1996 (= BSW96); Hofmann et al. 1998 (= HSW98)). From simple analytic considerations (Scholz 2001; Mennesson et al. 2002) and model-based CLV studies (e.g. HSW98; Jacob et al. 2000; Bedding et al. 2001; Jacob & Scholz 2002 (= JS02)), typical forms of brightness profiles may be distinguished in the optical to near-infrared wavelength region:

- **Small to moderate limb-darkening.** In pure-continuum bandpasses, CLV shapes are close to the UD (with some modification in the blue due to the influence of Rayleigh scattering; Scholz & Takeda 1987; HSW98). Small to modest absorption above the continuum-forming layers results in moderate limb-darkening in many cases. The FDD is a fair approximation and very often a better approximation than the UD for fitting visibilities.

- **Gaussian-type CLV.** Strong absorption in substantially cooler layers than the continuum-forming layers generates a Gaussian-like brightness profile in the Wien part of Planck functions. This effect is, in principle, independent of atmospheric extension but is more prominent in an extended atmosphere with high temperature contrasts between high absorbing and deep continuum-forming layers.

- **CLV with tail- or protrusion-type extension.** Quite modest absorption ($\tau$ noticeably smaller than unity) in an outer layer of an extended configuration generates a two-component CLV appearance in the Rayleigh-Jeans part of Planck functions, consisting of the inner near-UD CLV of the continuum disk and a tail-type extension of the absorbing outer "shell". Depending upon the geometric dimensions of this extension, visibilities may be moderately to strongly affected and even ”distorted”. As absorption increases and absorbing layers move closer to continuum-forming layers, tails resemble more protrusions of the inner CLV. The
Gaussian-like CLV appearance found by Perrin et al. (1999) probably is produced by this kind of protrusion due to H$_2$O contamination of the K bandpass continuum (JS02). Details depend on the geometric position and on the geometric and optical thickness of the absorbing ”shell” (cf. Tej et al. 2003).

*Uncommon CLV.* Uncommon brightness distributions that cannot be described in terms of a simple scheme and that are not found in conventional compact-atmosphere stars may occur, depending on wavelengths, for intricate atmospheric stratifications.

Clearly, complex shapes of the monochromatic brightness distribution require accurate multi-baseline interferometric data that cover a large range of spatial frequencies if sound information is to be extracted from observations. For instance, naive visibility fitting procedures may lead to physically meaningless diameter-type quantities (e.g. HSW98; Bedding et al. 2001; JS02).

### 3. MONOCHROMATIC INTENSITY DIAMETER AND FIT DIAMETER

The CLV is the only geometric information about the stellar disk the telescope receives. A diameter-type quantity that is defined in terms of the shape of the CLV is called an intensity diameter (Baschek et al. 1991). In the case of the optical solar disk, the position of the CLV inflection point is used for defining the photospheric diameter of the Sun (see, e.g., Minnaert 1953). This diameter is a wavelength-dependent quantity but $\lambda$ variations are minute in the optical wavelength region. Essentially, the inflection point marks the position of the steep CLV flank at the edge of a compact-atmosphere stellar disk with small to moderate limb-darkening. In principle, an intensity radius defined in terms of the position of this flank may be applied to stars when high-precision CLV reconstructions become available.

For Mira disks, pure-continuum brightness profiles have steep flanks which accurately mark the position of continuum-forming layers (e.g. JS02). Weak molecular-band contamination of the continuum usually results in a slightly more limb-darkened CLV which still has a steep flank suited for defining a physically meaningful intensity diameter, but other types of CLV shapes do also occur depending on wavelength and on the position and thickness of the absorbing layers. In particular, tail- or protrusion-type extensions of the continuum CLV lead to multiple inflection points and may even involve slight limb-brightening (cf. Scholz 2001; Mennesson et al. 2002; JS02). No recipe is known for predicting a priori the influence of weak contamination upon the brightness profile. Rather, a case-by-case investigation has to be performed.

In the case of Gaussian-type CLVs, the FWHM may be adopted as radius-type quantity describing the disk’s brightness profile. There exists, however, no straight-forward correlation between the FWHM or the position of the inflection point and the position of, e.g., the $\tau=1$ layer in the absorbing spectral feature that generates this Gaussian appearance (e.g. Scholz 1997, 2001; HSW98; Jacob et al. 2000).

We conclude that the definition of meaningful intensity diameters in terms of the shape of the intensity CLV may be very difficult or almost impossible in the light of many spectral features, even at near-continuum wavelengths. Extremely high accuracy of CLV reconstruction from interferometry would be required in order to determine whether and where meaningful radius points on the CLV do exist.

In principle, fit diameters which are obtained by fitting an observed visibility by the visibility of an artificial brightness distribution (UD, FDD, Gauss, ...) are a variant of intensity diameters because they define a diameter-type quantity in terms of the CLV shape. In the case of a simple brightness profile with small to moderate limb-darkening, both UD and FDD fits provide a good approximation of the position of the CLV flank. The model study of HSW98 shows that they typically do not deviate from each other by more than about 10 percent and that FDD fits tend to match the real CLV significantly better. It also shows that visibilities from Gaussian-like brightness profiles are very poorly approximated by UD or FDD fits and may readily be recognized by considering a wide range of spatial frequencies including the neighbourhood of the first null. Single-baseline interferometric observations may lead to physically meaningless UD or FDD fit diameters depending on the spatial frequency of the fit. Unfortunately, a Gauss fit only yields the width (e.g. FWHM) of the brightness decline but no direct information about the geometric dimensions of the stellar disk. Similar systematic studies of observed visibilities have yet to be performed, but the occurrence of Gaussian-like CLVs in certain bandpasses is well established (see references listed in Section 2).
Particular problems occur in case of a two-component appearance of the brightness distribution generated in the Rayleigh-Jeans (or near-maximum) part of Planck functions by modest molecular absorption in upper atmospheric layers (see Section 2). This situation is predicted by models in standard near-continuum bandpasses in the near-IR (e.g. H, K, L) and may lead to distorted visibilities, very poor UD fits and a strong baseline-dependence of fit diameters in case of single-baseline measurements. The relevance and interpretation of such diameters was investigated in the model study of JS02. High-precision interferometry should be able to identify such visibility forms and to extract information about the position of both the continuum-forming and the upper absorbing layers (JS02; Tej et al. 2003).

4. MONOCHROMATIC OPTICAL-DEPTH DIAMETER

The monochromatic optical-depth radius $R_{\lambda}$ is the distance of the $\tau_{\lambda}=1$ layer from the star’s centre. This radius definition is a standard definition in stellar models but no observable quantity. Since the radial optical-depth interval $d\tau_{\lambda} = -k_{\lambda}(r)\rho(r)dr = -dr/l_{\lambda}(r)$ ($\rho$ = density; $k_{\lambda}$ = extinction coefficient) measures the local distance interval $dr$ in units of the local photon mean free path $l_{\lambda}(r)$, this choice of radius definition means choosing the layer which is just one integrated mean free path below the “surface” of the stellar atmosphere. Unfortunately, however, photons collected by the observer often originate from a wide range of depths around the $\tau_{\lambda}=1$ layer, and there is no trivial correlation between the shape of the CLV curve and the position of $R_{\lambda}$ on that curve (e.g. Scholz 1997, 2001; Jacob et al. 2000; JS02).

Since optical-depth diameters are model quantities, they depend in principle not only upon the global stellar parameters (see Section 6) including phase and cycle of variability but also upon the quality of the model. We refer to the original papers regarding modelling approximations (Bessell et al. 1989; BSW96; HSW98; Höfner et al. 1998; Woitke et al. 1999) and only list the most critical points: (a) drive of pulsation (e.g. piston BSW96; self-excited HSW98); (b) dynamical density stratification resulting from shock-front-driven outflow and subsequent infall of matter; (c) non-grey temperature stratification which, in presently available models, is computed in the approximations of local thermodynamic and radiative equilibrium (cf. Beach et al. 1988 and Bessell et al. 1989 as for relaxation of shock-front-heated material); (d) completeness and numerical treatment of molecular band absorption, including serious and unsolved problems of applying opacity distribution function techniques (cf. Baschek et al. 2001; Wehrse 2002) and opacity sampling techniques, respectively, to a dynamic atmosphere with pronounced velocity stratification; (e) treatment of the transition zone from atmospheric to circumstellar layers (including dust formation).

Since intensity diameters are not accessible to presently available interferometric observations, and since the physical relevance of such intensity diameters is quite modest in many cases, measured fit diameters are usually converted into optical-depth diameters via model considerations. This requires, however, that models with suitable stellar parameters (including variability phase and cycle) are chosen and that sufficiently realistic models are available. Otherwise, derived optical-depth diameters are more or less formal quantities without sound correlation to the geometric structure of the Mira atmosphere. Generally, the conversion of a fit diameter into an optical-depth diameter tends to be safest in cases of steep-flank CLVs with $R_{\lambda}$ lying on the steep flank. In particular, real-continuum radii $R_{\lambda,cont}$ are perfectly marked by the flank position (e.g. JS02).

5. FILTER-INTEGRATED QUANTITIES

Real observations are done in bandpasses of finite width, i.e. a physically meaningful interpretation of secured data requires accurate knowledge of filter transmission $f_{\lambda}$ unless the CLV is $\lambda$-independent (e.g. pure continuum) inside the considered bandpass. No trivial correlation between the monochromatic CLVs inside a filter and the filter-integrated CLV exists. Obviously, high-intensity portions of the spectrum contribute more strongly to the CLV than low-intensity portions. This means that the integrated CLV tends to be dominated by contributions of deeper layers belonging to smaller monochromatic diameters.

The optical-depth radius of a bandpass may either be defined in terms of some mean value of monochromatic optical-depth radii $R_{\lambda}$ or in terms of a mean optical depth belonging to a mean extinction coefficient. The most common definition of the filter radius by Scholz & Takeda (1987) uses the central intensity on the disk $I_{\lambda}$ as weighting function of $R_{\lambda}$: $R_{f} = \int R_{\lambda}I_{\lambda}f_{\lambda}d\lambda/\int I_{\lambda}f_{\lambda}d\lambda$. For safe conversion of measured intensity or fit
radii into optical-depth radii, the filter transmission has to be known accurately. Bandpass radii based on mean optical depths are uncommon but are being used for defining "the radius" of the star averaged over all wavelengths (see Section 6).

Clearly, impure filters that contain a mixture of low-intensity and high-intensity spectral features are hardly useful for extracting information about the geometry and physics of the Mira atmosphere. Special care has to be taken in the choice of bandpasses that are to probe strong-absorption features of the spectrum. If these bandpasses have leaking transmission wings and intensities are substantially higher in the wings, the observation may be dominated by the weak-absorption features although the bandpass is centred in the strong-absorption feature and only contributions from this feature are within the FWHM bandwidth. This may happen, e.g., in the Wien part of Planck functions where the extreme temperature sensitivity of the source function results in extreme intensity contrasts between strong- and weak-absorption features.

Note in this context that picket-fence structures of certain molecular bands in which near-continuum gaps appear between strong lines also produce impure-filter-like effects, and the line spectrum of suspect molecular bands (e.g. CO) in the bandpass should be checked before starting an interferometric project.

6. MIRA AND PARENT STAR DIAMETER

The fundamental parameters of a variable star are the mass $M$, the time-dependent luminosity $L(t)$ and the time-dependent radius $R(t)$. In the case of an extended-atmosphere star such as a Mira variable, a sensible definition of "the radius" of the star has to be agreed upon. The most common definition refers to the position of the atmospheric layer where the radial Rosseland optical depth equals unity, $R = r(\tau_{Ross} = 1)$, and this definition is called the Rosseland radius. The effective temperature $T_{eff} \propto (L/R^2)^{1/4}$ of the star always refers to a specific radius definition.

Several caveats have to be noted. (a) The Rosseland radius is an optical-depth radius, i.e. it is a model quantity but no observable quantity. (b) The Rosseland opacity is a harmonic-type mean opacity weighting heavily the low-extinction portions of the spectrum. Its calculation may depend strongly on the completeness and numerical treatment of molecular band absorption (see Section 4). For instance, Rosseland opacities used for constructing interior models are often based on substantially more simplified molecular band contributions than those used in atmospheric models. (c) In most cases, the heavy weight of low-extinction contributions to the Rosseland average means that $R$ is close to the continuum radius $R_{cont}(t)$ which depends little on $\lambda$ (see Scholz & Takeda 1987 and HSW98 for effects of Rayleigh scattering in the blue) and is in principle observable by determining the position of the steep CLV flank (see Section 4). (d) At very cool phases, molecular absorption may blanket near-continuum windows so efficiently that the Rosseland mean increases significantly and the Rosseland radius is shifted into much higher layers than the continuum-forming layers (e.g. HSW98).

For these reasons, a sensible alternative definition of "the radius" in terms of a continuum radius may be preferred. Standard near-continuum bandpasses in the near-IR would be suited if slight to moderate molecular contamination is carefully accounted for (cf. JS02).

The above discussed radii are time-dependent quantities. If time-independent properties of Mira variables are investigated, such as the position and (slow) evolution in the HR-diagram, the period-luminosity-relation or the period-radius-relation, time-independent luminosities and radii have to be used. Whilst the time-independent luminosity $L_p$ is the time-average of $L(t)$, there exists no physically meaningful time-average of $R(t)$. Instead, the "parent star" of the Mira variable is considered. This is a hypothetical non-pulsating star with the same mass $M$ and luminosity $L_p$ as the Mira variable and with the Rosseland radius $R_p$. Models predict (BSW96; HSW98) that $R(t)$ may typically deviate from $R_p$ by up to about 10 or 20 percent, but larger deviations may occur at very low effective temperatures owing to the above mentioned behaviour of Rosseland opacities.

Note that the parent star is an artificial object, and deriving $R_p$ or any other radius of the parent star from observations is possible only via model considerations.

A wealth of interferometric measurements of "the radius" of M-type Mira variables has been reported in recent years (e.g. Karovska et al. 1991; Haniff et al. 1992, 1995; Quirrenbach et al. 1992; Ridgway et al. 1992; Wilson et al. 1992; Tuthill et al. 1994, 1995, 1999, 2000; van Belle et al. 1996, 1997 (S-type Miras),
2002; Weigelt et al. 1996; Bedding et al. 1997; Lattanzi et al. 1997 (HST observations); Burns et al. 1998; Perrin et al. 1999; Hofmann et al. 2000, 2001, 2002; Weiner et al. 2000 (mid-IR); Young et al. 2000 ($\chi$ Cyg); Mennesson et al. 2002; Thompson et al. 2002a, 2002b). The degree of elaboration of reduction of the measured fit diameter to a physically meaningful geometric size parameter varies greatly. Quite often, it is assumed that a UD-fit radius in a near-continuum spectral bandpass is close to $R_{\lambda\text{cont}}(t)$ as well as to the Rosseland radius $R(t)$ and, when the position in the HR-diagram or the period-radius-relation is considered, that $R_{\lambda\text{cont}}(t)$ or $R(t)$ is a fair approximation to $R_p$. Comparison of measured diameters and deduced effective temperatures from different sources has to account for the radius definition adopted by the observer. The fundamental problems of converting a Mira fit diameter observed in near-continuum bandpasses into a physically meaningful quantity and strategies of minimizing uncertainties are discussed in JS02.

The period-radius-relation was investigated by several authors (e.g. Haniff et al. 1995; Van Belle et al. 1996; Van Leeuwen et al. 1997; Whitelock and Feast 2000) and seems to point to first-overtone-mode pulsation of M-type Mira variables (cf., however, a different interpretation given by Ya’ari & Tuchman 1999). No strict reduction of measured data to the parent star radius was carried out in these studies. More recent work (e.g. Perrin et al. 1999; Hofmann et al. 2002; Mennesson et al. 2002; van Belle et al. 2002) and the model study of JS02 suggest systematically smaller radii to be inserted in the period-radius-relation and, hence, rather favours fundamental-mode pulsation in agreement with other pulsation-mode indicators (see, e.g., Wood et al. 1999; Scholz & Wood 2000).

Observations of the pulsation of a Mira, i.e. of the variation of the continuum diameter with phase were reported by, e.g., Tuthill et al. (1995, o Cet), Burns et al. (1998, R Leo), Perrin et al. (1999, R Leo) and Young et al. (2000, $\chi$ Cyg), but the problem of the influence of phase-dependent molecular contamination upon measured fit diameters is still not fully solved (JS02).

7. MODEL DEPENDENCE OF DIAMETER MEASUREMENTS

The only way of securing through interferometry direct information about the geometry and physics of a Mira would be the full reconstruction of the monochromatic or filter-integrated CLV at different wavelengths. These CLVs could be compared to model predictions. Such CLV reconstructions are not feasible in the nearest future. In practice, observers obtain fit diameters at different levels of sophistication and accuracy and have to convert these fit diameters into more meaningful geometric quantities via model considerations.

In the ideal case, a "perfect model" should be available that has the same fundamental stellar parameters ($M$, $L(t)$, $R(t)$) and the same variability phase as the observed star. In fact, as Miras show more or less pronounced cycle-to-cycle-dependence of the atmospheric structure, a set of such models covering a large number of cycles would be required. When neither the fundamental parameters of the observed star nor the characteristics of the cycle of observation are already known, the conversion of fit diameters into physically more meaningful diameters would have to be an iterative process.

At the present stage of Mira model construction, such models are far from being perfect (see Section 4; BSW96; HSW98; Höfner et al. 1998; Woitke et al. 1999), are available for only a very few stellar parameters, and cover only a few selected phases of a small number of successive cycles. Thus, interpretation of measurements and deduced "observed diameters" may be model-specific and may change when different models are used.

8. MIRA ANALYSIS BY INTERFEROMETRY

High-accuracy interferometric observations may not only be used to determine "the radius" of the Mira star (see Section 6) but may also serve as a tool of diagnostics of the geometric and physical structure of the Mira atmosphere. Since the atmospheric stratification depends on all fundamental stellar parameters ($M$, $L$, $R$), precise interferometry may also be used to obtain information about the otherwise unobservable stellar mass.

As the interpretation of measured data as well as the analysis of the atmospheric stratification are model-dependent, and as the correlation between this stratification and the stellar parameters has to be derived from a model, results are coupled to the availability of reliable models in the relevant ranges of stellar parameters and phase-cycle-combinations. In addition, high-accuracy interferometry in combination with spectroscopy (cf. Tej
et al. 2003) may be used to investigate the quality and possible shortcomings of Mira modelling approximations (see Section 4).

The most promising approach to interferometric Mira analysis consists of (i) simultaneous observations with different baselines (in order to explore the shape of the CLV), (ii) simultaneous observations in different bandpasses (in order to probe the momentaneous atmospheric stratification), and (iii) observations in the same bandpasses at different phase-cycle-combinations (in order to probe the time variation of the atmospheric stratification). Observations at the same phase of different cycles may be combined although cycle-independence may not be taken as granted and has to be checked in each case. Numerous observations in different bandpasses (though not always secured at the same time) have been reported in the past decade (e.g. Haniff et al. 1992, 1995; Tuthill et al. 1995, 1999, 2000; Weigelt et al. 1996; Burus et al. 1998; Hofmann et al. 2000, 2001; Young et al. 2000 (χ Cyg); Mennesson et al. 2002; Thompson et al. 2002b). No systematic attempts have so far been made to use such observations for analyzing the atmospheric structure. A very promising spectroimaging technique which provides direct access to molecular contributions shaping the disk brightness was successfully applied to o Cet (Takami et al. 2003). Model-based studies that discuss wavelength effects include, e.g., HSW98, Hofmann et al. (2000, 2001), Jacob et al. (2000), and JS02.

One of the most urgent and most rewarding observations for probing the Mira atmosphere would be the determination of the position of the shock front. So far, only one observational project was designed for this purpose and was not successful for technical reasons (P. R. Wood, private communication, contact wood@mso.anu.edu.au for information). The hot post-shock material is seen in the spectrum by typical emission lines, in particular the Balmer series of hydrogen. The hot zone is very narrow (Fox & Wood 1985), and its influence on atmospheric temperatures and photon fluxes is usually neglected in Mira models (BSW96; HSW98; see also Beach et al. 1988 and Bessell et al. 1989). Balmer-line fluxes are, however, strong enough to be accessible to high-precision interferometry (Fox et al. 1984; Gillet et al. 1983, 1985a, 1985b; Gillet 1988a, 1988b; Woodsworth 1995 (S-type Miras); Richter & Wood 2001). Line strengths vary strongly with phase (and cycle). In principle, any Balmer emission line may serve the purpose of measuring the shock front position, though Hα may be less suited because of much higher fluxes from the cool atmospheric material at this wavelength.

Another unsolved problem is the frequency, time-dependence and wavelength-dependence of observed deviations from circular symmetry of the Mira disk. Tentative explanations include, e.g., surface spots, non-radial pulsation modes and asymmetric shock fronts, patchy high-layer extinction, effects of a circumstellar dust or gas disk, rotation, and the influence of a companion star. Numerous observations of asymmetries have been reported in the literature (e.g. o Cet: Karovska et al. 1991, Haniff et al. 1992, Wilson et al. 1992, Quirrenbach et al. 1992, Haniff et al. 1995, Lattanzi et al. 1997 (HST), Tuthill et al. 1999; χ Cyg: Haniff et al. 1995, Tuthill et al. 1999; R Cas: Haniff et al. 1995, Weigelt et al. 1996, Tuthill et al. 1999, Hofmann et al. 2000; R Dor: Bedding et al. 1997; W Hya: Lattanzi et al. 1997, Tuthill et al. 1999; R Leo: Tuthill et al. 1999; R Tri: Thompson et al. 2002a), but little is known about phase-cycle-dependence or pulsation-independent time variation in given bandpasses and about wavelength-dependence at a given time. Systematic studies including closure phase measurements would not only reveal such dependences but would also allow to disentangle contributions to two-component CLV shapes generated by spherical molecular "shell" absorption (see Section 2) and by surface spots.

This review does not cover interferometry of the circumstellar environment of Mira stars. Still, one has to be aware that there is no real separation of atmospheric and circumstellar layers. Model makers use to choose the "surface" of the stellar atmosphere in terms of an estimated very small optical depth which is so small that both radiative energy transport and strongest spectral absorption features can be treated correctly. In the BSW96 and HSW98 models, the distance of this "surface" from the star’s centre ranges from $2R_p$ to $5R_p$ for different model series. In particular, the occurrence of dust in upper atmospheric layers or in the stellar-to-circumstellar transition layers would considerably affect brightness distributions (cf. Bedding et al. 2001). Interpretation of interferometric and spectroscopic data indicates, indeed, that the inner edges of dust shells might be as close as 2 or 3 continuum radii from the star’s centre (e.g. Danchi et al. 1994; Danchi & Bester 1995; Lobel et al. 2000; Lorenz-Martins & Pompaia 2000). Although the uncertainty of such values is hard to assess, it is evident from the exploratory model study of Bedding et al. (2001) that dust may form under certain conditions in upper
atmospheric layers and would show significant effects on brightness distributions and spectral characteristics in the optical to near-IR wavelength range with typical phase-cycle- and wavelength-dependence.

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