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The multi-wavelength view of Hot, Massive Stars: Concluding remarks

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Abstract: The papers in this volume demonstrate the importance of adopting a multi-wavelength approach to understanding hot, massive stars and their environments. They also reflect an excitement about recent developments in the field of massive star research that was so clearly evident during the meeting in Liège. Here I review some of the topics and results that were presented at the meeting that capture a sense of the emerging issues and opportunities in massive star studies.

1 Multi-wavelengths and multi-processes

We are truly living in the Golden Age of Astronomy, seeing for the first time the appearance of the sky across the electromagnetic spectrum. The profound influence of multi-wavelength observations is particularly evident in massive star research, and the work presented at this meeting dramatically illustrated the new insights we have gleaned from Earth-based and space-borne telescopes that give access to almost all wavelength bands. The second theme that resonated through the meeting was the importance of high angular resolution observations in illustrating the interaction between stars and their immediate environments. Table 1 (loosely borrowed from the presentation by Zinnecker) outlines in very broad terms the kinds of radiation sources we detect in different spectral bands, and it reminds us that we need to look beyond the optical band in order to discover the thermal and non-thermal emission from gas and to detect the radiation from the cooler dust component.

Table 1: Radiation Sources

Wavelength region	Physical origin
gamma-ray	winds, gas/cosmic rays
X-ray	hot gas, winds
UV/optical	stars, winds, H II regions
near-IR	stars, winds, embedded protostars
thermal-IR	disks in young stars
far-IR	warm dust
submillimeter/radio	cold dust, gas

A visually and scientifically beautiful example is the composite image of the RCW 49 H II region and embedded cluster Westerlund 2 shown in Figure 1. The black and white image shows the dust and line emission in the near-IR from *Spitzer* while the false colour inset shows the *Chandra* image of the young star cluster. The point sources include the very massive binary system WR 20a, a dozen early O-type stars, and a large number of pre-main sequence stars (Nazé, Rauw & Manfroid 2008). The central region surrounding the massive stars has been swept clear of dust by their radiation and winds. Images like this remind us of the profound interactions between massive stars and their surroundings, and it is through multi-wavelength investigations that we can begin to understand the co-evolution of stars and their environments. In this review, I will highlight some of the remarkable discoveries and insights that were presented at this meeting. Rather than cite each individual paper, I will simply refer to the lead author's name in my discussion of selected topics, and I hope this will encourage readers to seek out these contributions elsewhere in this volume.

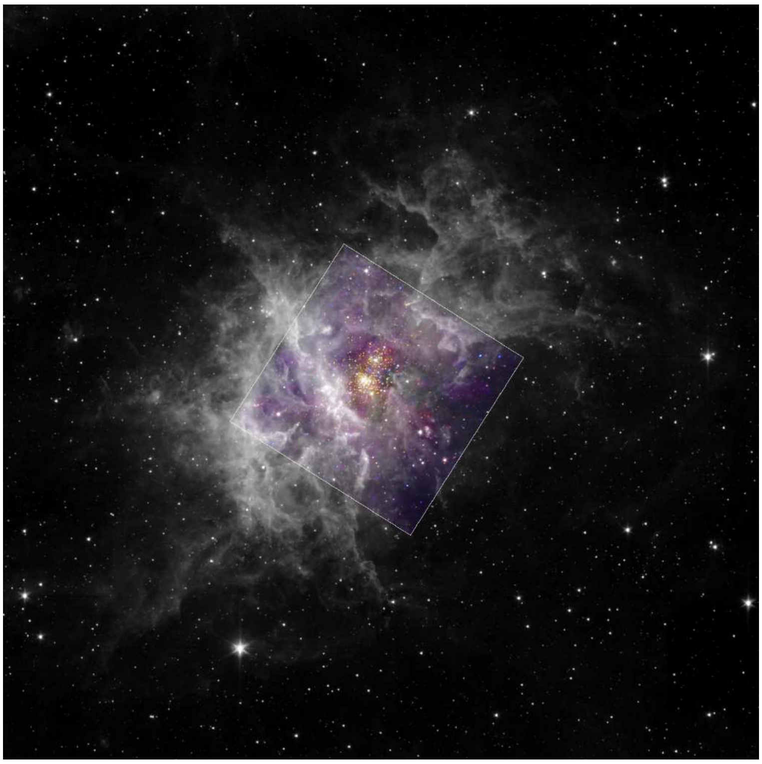

Figure 1: The young star cluster Westerlund 2 as seen in the infrared (*Spitzer Space Telescope*; shown in black and white) and in X-rays (*Chandra X-ray Observatory*; shown in false color). The hot stars and pre-main sequence objects within the cluster's central region shine brightly in X-rays. (Courtesy of Y. Nazé, G. Rauw, J. Manfroid, and E. Churchwell.)

2 Making massive stars

The primary sequence in the creation of a massive star includes the fragmentation of a giant molecular cloud, collapse and formation of an ultra-compact H II region, disk accretion onto a protostar, and dispersal of the remnant gas (Beuther). The theory of massive star formation has had to confront two fundamental problems: how gas accretion can occur in the presence of the radiation pressure and winds of a luminous protostar and how the natal gas angular momentum can be redistributed to permit accretion. We learned at this meeting of the substantial progress made through detailed magnetohydrodynamic simulations of the star formation process (Kuiper), its consequences for the surrounding nebula (Mackey), and the interaction between the winds of the disk and protostar (Parkin). Figure 2 shows an example of a recent three-dimensional simulation of the star formation process from Krumholz et al. (2009). This and other simulations show that massive accretion disks tend to fragment and form massive companions, so that much of the angular momentum is transformed into stellar orbital motion. Furthermore, gas accretion can occur despite radiation pressure through Rayleigh-Jeans instabilities that occur near the inner disk boundary. Such models suggest that effective gas accretion can form stars as large as $140M_{\odot}$ (Kuiper).

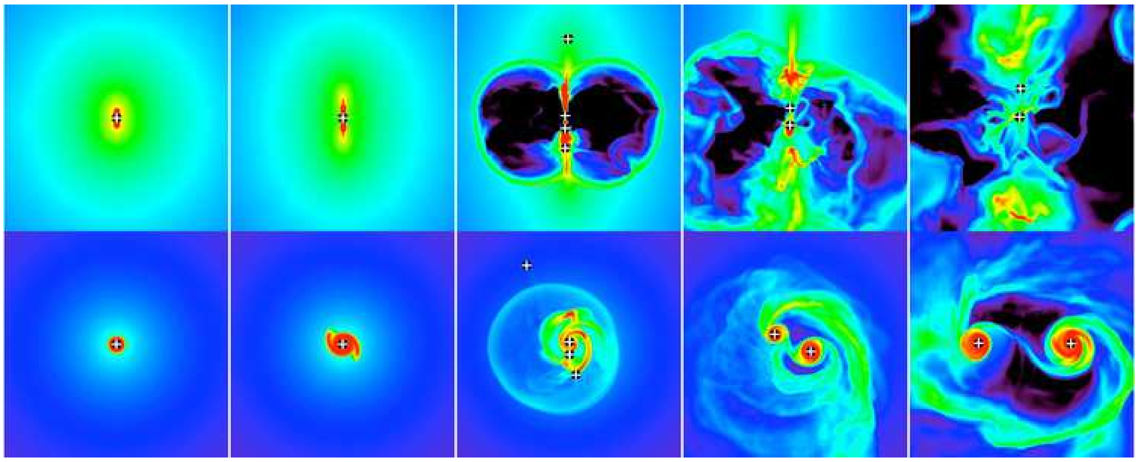

Figure 2: A simulation of the formation of a massive star (colour representing density) from Krumholz et al. (2009). Time progresses from left to right over an interval of 4×10^4 y. The top panels show an equatorial view, while a polar view appears in the lower panels. Plus signs indicate the projected positions of stars, and the two survivors had masses of $41.5M_{\odot}$ and $29.2M_{\odot}$ at the conclusion of the simulation. (Courtesy of M. Krumholz.)

Confronting the models with observations is particularly challenging, because most of the accretion onto massive protostars occurs while the young star is still deeply embedded in its very opaque natal cloud. Nevertheless, progress is being made in identifying objects with specific stages in the formation process and in understanding the consequences of these processes for the natal gas cloud. For example, Robitaille et al. (2006) and others suggest that young objects may be assigned to perhaps three evolutionary stages in a sequence of decreasing accretion rate: Stage I objects have infalling clouds and possibly disks, Stage II objects have optically thick disks with a continuing rain of infalling gas, and Stage III objects have optically thin disks. Individual massive young stellar objects (YSOs) can be related to these stages based upon criteria associated with their spectral energy distributions and spectral features (Chen). There is abundant indirect evidence of the predicted disks around massive YSOs from observations of bipolar outflows and IR excesses, and of the consequences of their radiation output in superbubbles, H II regions, X-ray heating, and maser emission (Beuther, Chini, Chu, Clark, Hummel, Hénault-Brunet, Ramsey, Selier, van der Walt). Direct evidence of disks may soon be forthcoming through long baseline interferometry methods. For example, Kraus et al. (2010) recently reported on VLTI/AMBER observations a $20M_{\odot}$ YSO with a flattened appearing circumstellar envelope.

3 Evolution and clusters

The story of how massive stars evolve from their birth in a dense cloud to death in a supernova explosion is assembled largely through detailed stellar interior models and their interpretation through the distributions of different kinds of stars in star clusters of different ages. The evolutionary models from the Geneva group (Meynet) are particularly successful in reproducing the primary features of stars in clusters. The main issues remaining concern the assignment of realistic mass loss rates at different stages of evolution and the treatment of the angular momentum redistribution in the interiors of rapidly rotating stars (Ekström et al. 2008). It is now clear that the evolutionary path of a single massive star depends fundamentally on its initial mass, metallicity, and rotation rate. Ekström et al. (2008), for example, show that the ratio of the equatorial to critical rotational velocities increases as a star evolves away from the zero-age main sequence. Luminous stars will probably encounter the so-called $\Omega\Gamma$-limit (Maeder & Meynet 2000) at even lower rotational velocities earlier in their lives, and such cases may correspond to the Luminous Blue Variables (LBVs), stars that experience large scale, eruptive, mass loss episodes. The mass and angular momentum consequences for the evolution of the star depend critically on the assumptions made about the variation in mass loss rate between the equator and poles of rapidly rotating, luminous stars (Lovekin, Meynet, Owocki).

A large fraction of massive stars are members of binary systems (Mason et al. 2009), and consequently, it is vitally important to consider how the presence of a close companion can alter a star's evolutionary path. Now, in addition to the fundamental parameters of the single star case, one must specify the binary properties of orbital period (or separation), mass ratio, and orbital eccentricity (De Mink, Vanbeveren). The evolutionary path of the binary will depend on both mass and angular momentum loss and transfer, so it is important to account for changes in rotation caused by tidal locking, Roche lobe overflow, and mergers (De Mink). It is helpful for investigating such a large parameter space to create distributions for all these input parameters and then to combine binary evolutionary codes with sampling of these distribution functions to perform a numerical population synthesis (De Mink, Vanbeveren). There are such diverse stages and outcomes for binary evolution that it is difficult to make comparisons with observational properties. For example, is a single, rapidly rotating star spun up by a change in the internal moment of inertia or by mass transfer from a companion lost by a supernova explosion? In such circumstances, it may be that stars in wide binaries offer the best examples of single star evolution, because we can reasonably conclude that they have not experienced mass exchange (De Mink).

The Conti-scenario (Conti 1976) for the formation of Wolf-Rayet (WR) stars through mass loss by stellar winds has stood the test of time, but there is now a realization that the WR phenomenon may represent more the state of a stellar atmosphere rather than a specific evolutionary stage. For example, there are now many known cases of WNL stars (those with some hydrogen in their atmosphere) among the most luminous stars in very young and massive clusters. These are probably extremely massive stars ($60-120 M_\odot$) that are "born evolved", i.e., without experiencing a prior red supergiant phase (Hamann, Liermann). Lower mass WR stars may have lost their H-envelopes by winds or Roche lobe overflow in a binary, but it appears that the wind loss rates are sufficient to create a WR star even at the low metallicity of the Small Magellanic Cloud (Pasemann).

A critical test of stellar evolutionary models is to consider the numbers and kinds of supernovae predicted based upon an assumed Initial Mass Function for massive stars (Smith). This approach shows some disagreements with our simple expectations (Smith et al. 2011). For example, the mass range of WR stars that lose their H envelopes by winds makes up less than half the observed fraction of SNeIbc, those supernova lacking H but otherwise occurring among massive populations. This suggests that a significant fraction of SNeIbc progenitors lost their H-envelopes through binary mass transfer.

Star clusters remain the fundamental means to test the evolutionary tracks for populations with a well defined age and to search for evidence of dynamical processes such as mass segregation and the ejection of runaway stars. Observational programs on clusters are well advanced and have focused on very young and dense clusters like 30 Dor (Hénault-Brunet, Taylor), the Quintuplet Cluster near the Galactic center (Liermann), Westerlund 1 (Dougherty, Ritchie), the Cyg OB2 association (Caballero-Nieves, Kobulnicky, Willis), M17 (Chini), and the Carina region (Kumar). Surveys, particularly in the infrared, have led to significant progress on other clusters in the Galaxy (Clark, Edwards, Mahy, Marco, Ramírez Alegría) and beyond (Bomans, Bonanos, Sholukhova, Wofford).

4 Winds and outflows

The CAK theory of the radiatively driven winds of luminous stars (Castor, Abbott & Klein 1975) remains central to our understanding of mass loss, and we are still exploring its ramifications for wind structure (Owocki). Radiatively driven winds are inherently susceptible to a line-shadowing instability that leads to the formation of small dense clumps in the wind, and the presence of wind clumping can radically influence the mass loss rates derived from diagnostics based upon density-squared. In some circumstances, large scale, optically thick structures may form in the wind, and the resulting "porosity" affects diagnostics that depend linearly on density. The challenge ahead is to develop time-dependent dynamical wind models to study the development of structure in the wind and to determine how such structures influence different measurements of the mass loss rate (Hamann, Lobel, Owocki, Sundqvist, van Marle). Puls et al. (2006) found that the clumping factor may have a radial density dependence, so a single value of the clumping factor may be inadequate to describe the whole wind. Models were presented at the meeting that describe how clumping affects the interpretation of optical and UV features (Sundqvist) and X-ray diagnostics (Hervé, Oskinova).

Rotation plays an important role in the mass loss rates, and current models suggest that in a rapid rotator, the wind is slower and less dense at the equator and is faster and more dense at the poles (Lovekin, Meynet, Owocki). The fact that we often observe dense equatorial outflows around luminous stars (for example, the skirt region in η Car) indicates that other mechanical processes are at work in addition to radiative driving. One explanation for the ejection of equatorial disk gas in Be stars is the combined action of rapid rotation and stellar pulsation (Cranmer 2009). Pulsations or other azimuthally distributed perturbations may create Corotating-Interaction Regions that alter the wind velocity law and lead to accelerating Discrete Absorption Components in spectral lines formed in the wind (Lobel).

We now have a very rich set of observational results on mass loss diagnostics based upon the spectral line shapes and spectral energy distributions (Gräfener, Martins, Pasemann, St-Louis, Sander, Williams). X-ray measurements of the mass loss rate have assumed a new importance (Nazé, Oskinova) especially since there are now large samples of OB stars in the Second XMM-Newton serendipitous source catalogue (Watson et al. 2009) and the Carina complex survey (Gagné et al. 2010). Radio flux measurements are available for many stars, but these may be complicated by the presence of a non-thermal component from colliding winds in binaries (Blomme, Dougherty, Romero). Intrinsic polarization estimates are needed to study departures from spherical symmetry in the wind (Hoffman, Lomax).

A number of investigators have monitored selected sources to follow the photometric and spectroscopic variations due to clumping and other structural changes in the circumstellar environment (Buemi, Burggraf, Clark, David-Uraz, Grundstrom, Morel). These studies indicate a great deal of diversity in atmospheric and mass loss properties, but it may well be that deep seated photospheric changes may ultimately drive structure in the wind. For example, pulsational modes in rotating stars (Englebrecht) may attain large amplitude near the equator and promote mass loss there. More generally, higher order, multi-mode pulsations may increase the turbulence in the photosphere (Simon-Diaz), and turbulence may help seed instabilities in the wind that drive clumping.

The radiation and winds of luminous stars will help sculpt the ionization zones and density variations in the surrounding medium (Mackey, Pellegrini, Zastrow). The mass loss effects on the environment are most striking in more evolved, luminous stars where we observe the results from an entire stellar lifetime and we can study "mass loss archeology" from the radial distribution of the ejected gas (Hoffman, Smith, Umana). Wind gas may be swept up into a dense shell if a fast wind develops after a slow wind episode (van Marle, Smith), and we observe such shells in many LBV, WR, and B[e] stars (Bomans, Chu, Stock, Umana, Vamvatira-Nakou, Wachter, Weis). These shells are especially prominent in *Spitzer* 24μm images of evolved, massive stars (Wachter et al. 2010). Multiple outer shells and dust disks may also be detected when the star explodes as a supernova and first illuminates them and then sweeps them up as the blast wave moves outwards (Hoffman, Smith).

5 Rotation and magnetism

The fastest rotating massive stars are generally found among the emission line Be stars, where the equatorial velocities are perhaps $70-90\%$ of the critical velocity (Grundstrom, Martayan). If these stars are able to maintain some fraction of their angular momentum up to the time of the supernova, then it is possible that the core collapse will result in a short phase of disk and relativistic jet formation that is associated with long duration gamma-ray burst sources (Martayan).

On the other hand, we often find that slow rotators are stars with measurable magnetic fields (Morel). The number of magnetic detections is growing thanks to the concerted observational effort of the consortium on *Magnetism in Massive Stars (MiMeS)* [2] (Wade et al. 2008). Magnetic fields in early-type stars apparently act like those in late-type stars to spin down stars over their lifetime. A noteworthy example is HD 191612, a magnetic star and spectrum variable with a rotation period of 538 d (Howarth et al. 2007). Magnetic fields may also alter the star's wind properties (sometimes in spectacular ways; Townsend, Owocki, & Groote 2005). If magnetic reconnection acts to increase the X-ray generation, then the wind gas may appear overionized for the star's temperature and be classified as a "weak wind star" (Austin, Garcia). Curiously, a few magnetic stars are rapid rotators, and these must either be very young or recently spun-up stars.

6 Individual and binary stars

The fundamental parameters of many massive stars are now well established thanks to very careful spectroscopic analyses (Doran, Martayan, Martins, Przybilla, Simon-Diaz). These investigations yield the stellar effective temperature, mean gravity, projected rotational velocity $V \sin i$, and estimates of the photospheric micro- and macroturbulence. Macroturbulence may be a manifestation of multi-mode pulsations that are too complex to detect in the integrated stellar flux or spectral lines (Simon-Diaz). Surprisingly, the most massive stars ($50-200M_{\odot}$) all tend to have similar spectral types (O2-3 or possibly WNL) and may appear as luminosity class III or I objects even when very young (Doran).

With reliable fundamental parameters in hand, it is possible to obtain good estimates for the photospheric abundances of He, C, N, O, and other elements (Heap, Nieva, Pavlovski, Przybilla, Simon-Diaz). The measurements are especially useful for the reconstructed spectra of eclipsing binary stars, where independent estimates of stellar mass and radius are available (Pavlovski). Internal mixing in

[2] http://www.physics.queensu.ca/~wade/mimes/MiMeS_Magnetism_in_Massive_Stars.html

massive stars should bring CNO-processed gas into the photosphere causing the [N/C] ratio and He abundance to increase with time (Przybilla). Naively, we would expect mixing to be more vigourous in rapidly rotating stars, but there is no obvious correlation between [N/C] and $V \sin i$ in observational data from the VLT FLAMES survey. This diversity in abundance patterns hints that processes related to magnetism and binarity are at work (Morel).

The determination of stellar masses from binary orbits continues to be of central importance (Antokhin, N. Evans, Gies, Kobulnicky, Mahy, Nazé, Pavlovski, Vilardell). The current record holder is NGC 3603 A1a with a mass of $116 \pm 31 M_{\odot}$ (Schnurr et al. 2008), although there are a number of candidates with even larger mass based upon luminosity estimates and evolutionary models (Crowther et al. 2010). There are a number of impressive studies in these proceedings of selected "extreme stars" including supergiant B[e] types, hypergiants, and massive X-ray binaries (Aragona, Blay, De Becker, Martayan, Mason, McSwain).

The power of stellar winds assumes new forms in colliding wind binaries that offer us an extraordinary laboratory to study wind physics (Williams). Both analytical and smoothed-particle hydrodynamic models are now available that are valuable guides to the observations of colliding wind systems (Montes, Parkin, Pittard, Volpi). These models predict the spectral features and X-ray and radio emission as a function of orbital phase for eccentric orbit systems. One of the more remarkable predictions is that energies in the collision zone may be sufficient to create very high energy gamma-rays through π^0-decay of accelerated hadrons interacting with the dense stellar wind gas, and such a high energy component has now been identified in *Fermi* data on η Car, announced as a "very large hadron collider" in the sky (Farnier, Walter & Leyder 2011). It is now well established that η Car is a binary of two massive stars in a 5.54 y eccentric orbit. The two stars recently attained closest approach during a periastron passage in early 2009, and the colliding winds model appears to be consistent with most of the optical and X-ray spectral variations observed around that time (Corcoran, Groh, Madura, Parkin, Russell). The other famous colliding winds binary is WR 140, which also has an eccentric orbit, in this case with a period of 8 yr (De Becker, Dougherty, Fahed, Morel, Parkin, Sugawara, Williams). The colliding winds zone is a strong radio source in this binary and its positional variation with the orbit is detected in VLBA observations (Dougherty). There are many more colliding wind systems that are now under investigation in different wavelength bands (Blomme, Combi, Dougherty, Fauchez, Gosset, Nazé, Williams).

7 Future opportunities

We are entering a new era of extremely large, optical/IR telescopes (LSST, GMT, TMT, ELT) that will have superb instrumentation and extraordinary capabilities (C. Evans). They will help us find and characterize Galactic massive stars with large extinction and will make possible detailed studies of individual stars in nearby low metallicity galaxies (Bomans, C. Evans, Heap). At longer wavelengths there will be many new opportunities with ALMA, SKA, EVLA (Dougherty), and e-merlin (Willis). Among space missions, some of the first and very promising results are now available from Herschel (Vamvatira-Nakou), and we can anticipate future missions including JWST, GAIA (Damerdji, Palate), IXO (Hervé, Rauw), and BRITE (microvariations of bright stars; Chené). Many of the special targets among the massive stars are relatively bright and can be observed even with small aperture telescopes with good instrumentation (such as the spectrographs for small telescopes built by Shelyak Instruments). Professional – amateur collaborations hold great promise for extended observing campaigns on selected targets (Eversberg), such as the recent ConVento group collaboration on WR 140[3]. We are also entering an era of large scale surveys, and we will need to develop tools to present and mine

[3] http://www.stsci.de/convento/

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databases (Nieva, Ramsay, Simon-Diaz, Sota) and to create and distribute software to deal with the interpretation of vast new data sets (Garcia, Hanson).

Beyond the new multi-wavelength dimension, we now have the means to explore the spatial characteristics of massive stars and their environments at very high angular resolution thanks to developments in optical long baseline interferometry[4] (VLTI, Keck, NPOI, CHARA; plus future instruments like MRO and CARLINA; De Becker). Figure 3 shows a remarkable example of results from high resolution work, images of the components of the interacting binary β Lyr from H-band interferometry with the CHARA Array (Zhao et al. 2008). This binary consists of an evolved, B-type star (darker component) that is actively transferring mass to a companion, hidden in an extended accretion disk (lighter component), and these images probably represent our first resolution of an accretion disk in a Roche lobe overflow binary.

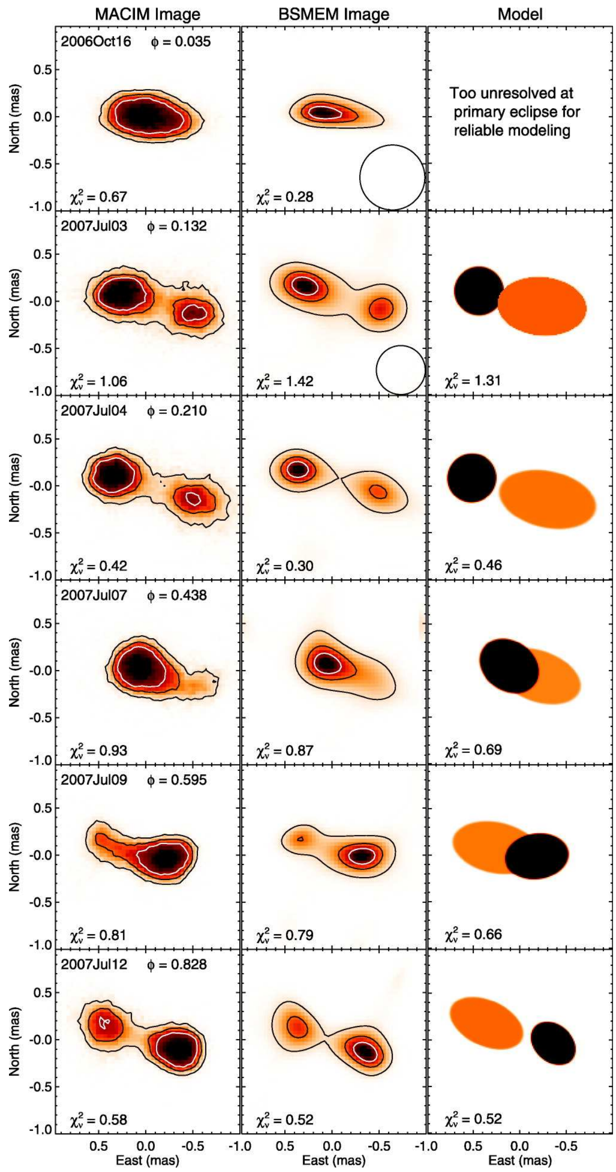

Figure 3: Image reconstructions of the interacting binary β Lyr from CHARA Array observations (Zhao et al. 2008). The six rows show the results from different binary phases while the three columns indicate two image reconstruction methods and a geometrical model fit. (Courtesy of M. Zhao.)

[4] http://olbin.jpl.nasa.gov/

8 A word of thanks

This meeting was a huge success in providing us with a venue to compare research results from across the spectrum and to better appreciate the methods and opportunities available at other wavelengths. The meeting brought together some 138 astrophysicists from around the globe, and I think that its impact will be significant and widespread (following in the tradition of earlier Liège astrophysical colloquia). The participants will long remember how we enjoyed World Cup football, the dramatically changing weather, and the companionship of colleagues and excellent hosts. This success was due to the support of the Université de Liège and other sponsors, the commitment of the Scientific Organizing Committee, and the hard work of the Local Organizing Committee. I would like to express my gratitude to all the meeting organizers and especially to the chairmen of the meeting, Gregor Rauw and Peredur Williams, for their vision and leadership. Finally, I extend our thanks to Yaël Nazé and Gregor Rauw's baby[5] who delayed her arrival until after the conclusion of the meeting.

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