White Paper on MASSIVE STARS for 2010 CASCA/LRP

Preamble

Massive stars are usually taken to be those with initial masses above ∼8 $M_\odot$ at ∼solar metallicity [5]. In contrast to their medium-mass cousins, which end their lives without completing all phases of nuclear burning as white-dwarf degenerates, massive stars generally only reach a degenerate state in their Fe-rich cores after all possible previous nuclear burning has taken place.

Most massive stars follow the evolutionary scheme: O→RSG/LBV→WR→SN→NS/BH/nothing, depending on the inital mass. In some rare cases a γ-ray burst is associated with the SN (type Ib/c).

Despite their relatively small numbers, massive stars dominate the ecology of the Universe, i.e. they are the main sources of energetic, recycled matter at all stages of the Universe. This was especially the case during the first generation of star-formation starting ∼ 0.4 Myr after the Big Bang, i.e. the so-called population III, with characteristic mass ∼100 $M_\odot$ compared to ∼1 $M_\odot$ for population II [14]. Such massive stars, with essentially zero initial metallicity, spend most of their lifetimes in a very hot stage, thus along with supernova, dominating the re-ionization of the Universe after the post CMB Dark Ages [14]. Massive stars are also the progenitors of both slow (single, rapidly rotating WR stars) and fast (fusion of binary NS-NS or NS-BH pairs) γ-ray bursts, which were more frequent in the early Universe. But even in today's Universe, massive stars produce the lion's share of processed matter and interstellar mixing/energizing, not only from the supernova explosion at the very ends of their lives, but also during their whole lives, brief as they may be (several millions of years), in the form of rapid, strong stellar winds. Besides their high masses, these winds are a defining feature of massive stars.

Past accomplishements

Below we outline several discovery highlights in the area of Massive Stars involving Canadian astronomers during the past decade (2000-2009). Space limitations prevent this list from being complete.

MOST, Canada's first astronomical satellite. Launched in 2003 June, one of MOST's (Microvariability and Oscillation of STars) original goals was to explore the micro-variability properties of Wolf-Rayet stars. Among the most exciting results found so far include the first discovery of a pulsation period in a cool WR star [15], and contrary to expectations complete lack of long-expected strange-mode pulsations in a hot WR star at a level nearly two orders of magnitude below current predictions [22] (see Fig. 1). Several OB stars (WR progenitors) have also been examined, e.g. with the first detection of g-mode pulsations in a blue supergiant [26]. All of these have important implications in understanding the interior structure of massive stars.

First detection of magnetic fields in O stars. Thanks to generous attribution of guaranteed time with the world's most powerful spectropolarimeter Espadons at CFHT, the newly created MiMeS collaboration led by G. Wade has significantly increased what we know about global magnetic fields in hot massive stars. Although the global detection rate is low (interesting in itself), we now know 3 O stars with order kG fields, including the brightest star in the Orion Trapezium, θ Ori-1 C [9] - see Fig.2. This reveals for the first time that the most massive stars can also have magnetic fields, probably fossil in nature, which lead ultimately to the gigantic field in neutron stars (10^{12}-10^{13} G).

Most massive star ever weighed. It has recently been realized that the most massive stars in the Local Universe tend to be of type WN5-7h/ha, showing WR-like emission lines (as a direct result of strong, hot winds driven by extreme radiation-pressure) but with nearly solar H and even hotter and more luminous than the upper MS defined by the hottest O stars. While no O star has been found to exceed 60 $M_\odot$, some WN5-7h/ha stars have been found to exceed 100 $M_\odot$. The WN6ha star A1 in the Galaxy's most massive, compact cluster, NGC 3603 (see Fig. 3), has a binary-determined (the least model-dependent technique) mass of 114 $M_\odot$. Such findings are important in the context of star formation close to the Eddington limit. A study of this cluster with Chandra [21] shows enhanced X-ray emission from A1 and especially star C, another of the 3 WN6ha stars in the cluster core and a short-period binary, but with the strongest known X-ray flux of any Galactic MS star.

Rotation rates of WR stars. Given the prediction that the immediate progenitors of slow GRBs are likely rapidly spinning WR stars, it is essential to attempt to determine the rotation rates of WR stars in general. Fortunately, there exist some WR stars with large-scale rotating structures in their wind, whose periods can be determined by identifying repeating spectroscopic features. A search for such effects in a systematic, viable sample of WR stars has been initiated for the first time [28]. Among the several rotating candidates found, the surface rotation rates (e.g. WR1: [4]) appear to be relatively small, implying that rotation is probably not an important factor in producing the strong winds of WR stars and that the bulk of WR stars do not become GRBs.

Understanding colliding hot-star winds. In massive binaries, the two strong winds collide and produce copious high-energy [6] and non-thermal radio radiation [8] (see Fig.4). The Rosetta Stone of colliding wind (CW) systems is WR140, an 8-year WC7d+O5 binary in a highly elliptical orbit (e = 0.88). Most of the interaction occurs over several months around periastron passage, which was observed during campaigns in 2001 [18][30] and 2009 (Fahed et al., in prep.). This has led to a greater understanding of colliding winds, in this case along with the formation of C-rich amorphous dust grains. As for the persistent dust makers of type WC9d, stunning MIR images have been obtained at the Gemini telescopes [20] (e.g. see Fig. 5), allowing to constrain the dust properties and formation mechanism. Analysis of the X-ray flares in the RXTE light-curve of the massive 5.5-year, highly eccentric (e ∼ 0.9) LBV binary system η Car (see Fig. 6) has shown that these are likely due to wind clumps from the LBV entering the CW zone [22].

First spectroscopic analysis of an extra-galactic giant LBV eruption. The extragalactic giant HII region NGC2363 (D=3.4 Mpc) was the host of a dramatic LBV eruption in 1996 [10] - see Fig. 7. A spectroscopic follow-up of NGC 2363-V1 with HST's STIS covering a wide wavelength range (115 - 900 nm) until 2004 (see Fig. 8) allowed this group to determine the spectacular evolution of the star's radius, mass-loss rate, surface temperature and luminosity.

Systematic studies of young open star clusters - the prime seat of massive-star formation. Besides making significant advances in the Cepheid PL calibration, D. Turner completed a study of the peculiar star content of the cluster Berkeley 87, host to the Galaxy's strongest-line WR star WR142 of type WO2 and the site of the strongest sources of cosmic rays in the northern hemisphere. Other young open clusters studied by Canadians include the GHR NGC 3603 (multi-wavelength study in X-rays, optical and radio: [21]), NGC 7419 (peculiar RSG/BSG ratio: [3]), and several others.

Starbursts and galaxy evolution. Massive stars are found in large numbers in starburst regions of galaxies, comprising GHRs, blue compact galaxies, nuclear starburst galaxies, ultra-luminous IR galaxies and Lyman-break galaxies at high redshift. Starbursts, best observed in the intrinsic UV, are important agents which sculpt galaxy morphology and allow us to follow the evolution of galaxies over the whole Universe. Robert and Dissen at U. Laval use massive stars to trace star formation in distant galaxies, where stars cannot be observed individually. They have contributed to the evolutionary synthesis code Starburst99 [16][17] and LavalSB [7]. In nearby regions, where massive stars may be identified individually, the synthesis technique represents an important test for stellar evolution and atmospheric models.

UV studies of individual stars. FUSE was used to examine the wind-wind collision in several WR binaries [27] [2]. [19] were able for the first time to establish a link between universal wind-clumping in hot-star winds and shock heating. Finally, Henault-Brunet et al. (submitted) have used FUSE to constrain the variability origin of the peculiar WR star WR46.

Current State and Health of the Discipline

On the international scene, massive stars have become recognized as key players in various stages of the Universe, as noted above. Although an informal international Working Group for hot stars was formed in the 1980's, it was only in the late 1990's that an officially supported IAU WG for Massive Stars (i.e. hot and cool stars of high luminosity) was created, where several Canadians continue to be members of the Organizing Committee. Today, this WG has over 400 members worldwide, connected by a bi-monthly electronic Newsletter and frequent exchanges, workshops and symposia, some of which have taken place in Canada.

Table 1 lists those Canadian astronomers whose research activity involves Massive Stars, and who are cosignatories of this White Paper. Those with permanent appointments normally supervise several graduate students/postdocs, making for a viable Canadian community involved in the study of Massive Stars.

Many exciting forefront projects are currently underway among Canadian astronomers in the area of Massive Stars, some of which include:

Search for WR stars in our Galaxy and other giant spirals. The development of one of the world's largest NIR imagers, CPAPIR in the Lab for Experimental Astrophysics at UdeM, allowed Shara (AMNH), Moffat et al. to undertake a large NIR survey for WR stars in the whole Galaxy. Narrowband search-imaging is now complete (6 months of time on the 1.5m at CTIO) and already 100 new WR stars have been spectroscopically confirmed, with well over 1000 other candidates waiting to be spectroscopically verified. Meanwhile, they have also started using HST optical narrowband imagery to find large numbers of WR stars in external spiral galaxies, for which 8m and larger class telescopes will be necessary to spectroscopically confirm and quantify their properties. Both of these projects will considerably improve our understanding of star formation galaxy-wide, with emphasis on the effects of varying ambient metallicity, and indentifying potential precursors of SNIbc (and maybe even a GRB with any luck), for which WR precursors are suspected but so far never confirmed.

First attemps to detect magnetic fields in WR stars. Given the large magnetic fields observed in Neutron Stars, it is likely that their *immediate* progenitors, WR stars, would have detectable fields at the ~ 100 G level at the base of their observable winds, assuming the fields are frozen in the collapsing plasma. Using Espadons at CFHT, UdeM PhD student de la Chevrotière is analyzing data for 11 of the brightest WR stars in the sky accessible from CFHT.

WR Colliding-wind dust makers. There is strong suspicion that it takes the extreme compression and associated shielding from the lethal stellar UV radiation in colliding winds, to allow dust to form in some C-rich WR stars. A number of dust-emitting WR stars are being spectroscopically monitored by St-Louis et al. for spectroscopic variability over days/weeks/months/years mainly on smaller telescopes, where such dedicated searches can be readily made.

Synthesis of distant young stellar populations in the UV. Starburst UV lines are sensitive to massive star properties and therefore allow one to estimate the age, metallicity, IMF and star-forming history of starbursts. [24] have shown that the far-UV regime, based on the synthesis of 24 starburst galaxies, is less sensitive to age-metallicity degeneracy effects. Also, in the far-UV, it is easier to isolate, in the integrated spectrum of a galaxy, a single and young stellar population. The study of the broad component seen at the base of nebular emission lines in the spectrum of NGC 2363 by [1], is a nice application of the synthesis models.

Future Prospects

Canadian astronomers working on massive stars are planning numerous future projects of which a few are listed below. They often involve instrumentation that is still being developped.

BRITE–Constellation. This is a Canadian nanosatellite project that germinated in the early 2000's and has led to two other countries joining the effort (Austria & Poland). First launch by ISRO (India) is foreseen for early/mid 2011 for the first two nanosats financed by Austria, to be followed later by 2 more from each of the other partner countries. All 6 nanosats will be used in a complementary way with 3 different filters to obtain unique ultra-high, long-term, precision photometry to study the pulsation properties of the brightest stars in the sky on hourly to several-month timescales. These stars, spread out all over the sky and difficult to observe this way from the ground, are also among the *intrinsically* brightest stars, with a significant fraction also massive. The results of rapid photometry in combination with groundbased spectral data on massive stars will provide a solid basis for stellar interior models. This will be the first time that nanosats will be used for astronomy - a first also for Canadian industry and technology.

Mass-loss rates for a large number of massive stars. The simplest and most reliable way to obtain one of the key parameters for massive stars, the mass-loss rate (after correction for clumping), is via multi-frequency radio observation in the mm/sub-mm range dominated by thermal emission. Current radio/mm telescopes are limited by small surface areas, so **ALMA**'s large mm/sub-mm array will open up a whole new game for massive stars in our Galaxy and the MCs. Complementary to this, it may be possible to study the detailed structures in stellar winds of the nearest stars through direct **VLBA** imaging. Wind clumping is clearly present, although its true nature remains obscure.

Theory and models. To simulate and match massive-star spectra including absorption and emission features, appropriate stellar atmosphere models are planned by V. Khalak to be calculated using the PHOENIX code [14]. The cose is specially designed to calculate models with strong stellar wind, assuming LTE or NLTE for many chemical species and molecules. In Victoria, Falk and post-doc Marco Pignatari are taking a leading role in the NuGrid nucleosynthesis collaboration. NuGrid is about comprehensive nucleosynthesis yield calculations for both low-mass and massive stars, as well as eventually explosive yields (e.g. http://forum.astro.keele.ac.uk:8080/nugrid).

Massive stars and the evolution of young star clusters Massive stars and their strong winds play an inportant rôle in the disruption and dissolution of young star clusters, possibly leading to OB and X-ray binary field stars. To date, very few studies have attempted to detect young dissolving clusters, and high spatial resolution images from HST/ACS were required to detect the candidate clusters [25]. To study such systems, one needs to use large telescopes capable of both detecting faint sources and spatially resolve them from the UV to the near-IR range (e.g. with HST, JWST, and TMT).

Starbursts in the UV, X-ray and visible. The Ultraviolet Imaging Telescope (UVIT), an Indian/Canadian endeavor, is expected to be launched in 2010 along with four X-ray instruments as part of ASTROSAT. ASTROSAT will operate in various high energy bands while UVIT will simultaneously provide UV and visible flux-calibrated images with a $\sim 1''$ spatial resolution and a 0.5o field of view [29]. In order to efficiently use UVIT to observe starbursts, filters will be defined to obtain reliable parameters. Simulations for more distant, redshifted galaxies will also be done. The reliability of the starbursts analysis will be tested on archival GALEX and HST UV images. Overall, questions rekated to SF regions will be addressed, e.g. looking at the age- or metallicity-separation relation between SF regions in galaxies with different properties, calculating the mechanical energy from stellar winds and supernovae while studying sequential SF, blowouts and more global processes. SpIOMM, a visible Fourier transform spectro-imager, is available at Megantic Observatory [11] and its successor SITELLE is being developed for the CFHT. The spatial capabilities of these instruments are well suited for a detailed comparison of the young UV populations seen in GALEX and soon UVIT images.

Properties of the First Stars. Although even the brightest First Stars will not be observable individually, they will be observable in giant starbursts in the IR using **JWST** for high-resolution deep IR imaging from space and **TMT** for follow-up spectroscopy. On the other hand, second generation, metal-poor stars formed after the first stars should be found locally in the Galactic Bulge and nearby dwarf galaxies [13]. TMT will be necessary to obtain spectra of these faint stars.

Future Instrumental and Other Needs

1. Better access to long-term temporal monitoring over daily/weekly/monthly/yearly timescales (optical/NIR photometry/spectroscopy, e.g. with small telescopes at good sites).
2. Better/more science support for space astronomy (e.g. postdocs to work with BRITE data).
3. Participation in large-telescope space missions, e.g. Astro-H and IXO for X-ray observations of luminous hot stars and their interaction with other such stars, compact companions or the ISM
4. JWST MIR imaging to find and study the First Stars
5. ALMA multi-frequency imaging to constrain mass loss from massive stars
6. Use of TMT to obtain high S/N, high spatial and spectral resolution, optical/NIR spectroscopy of individual extragalactic targets
7. Use of TMT to obtain ultra-high S/N spectropolarimetry of moderately bright stars
8. Continue large surveys, e.g. Galex, CFHTLS, SDSS and future ones: LSST.
9. Spectropolarimetry at CFHT with SPIROU in the near-infrared.

N.B. Especially important for the study of luminous, hot stars is the availability of UV spectroscopy from space for local objects and similarly optical/IR spectroscopy for extreme redshifted UV.

However, no matter what new instruments become available, we believe that there is a more serious problem regarding manpower. Who is going to use all these wonderful instruments? Clearly, astronomy in Canada needs a significant boost in qualified personel.

TABLE 1
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Figures

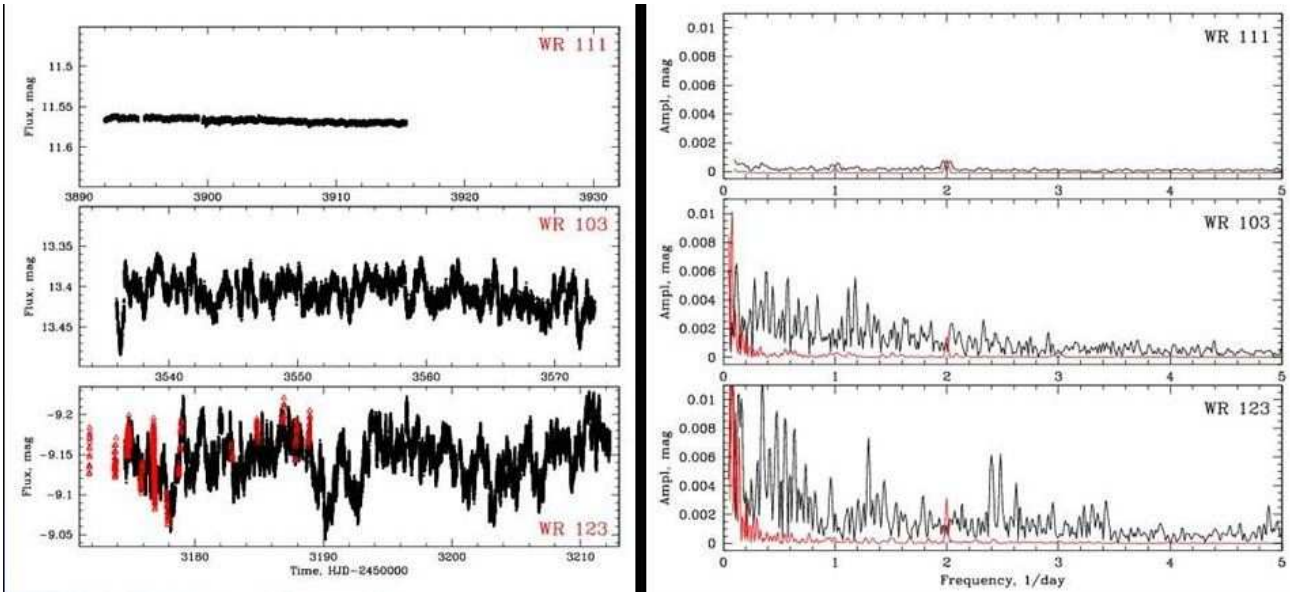

FIG. 1.— Lightcurves and Fourier spectra of the first three WR stars observed by MOST.

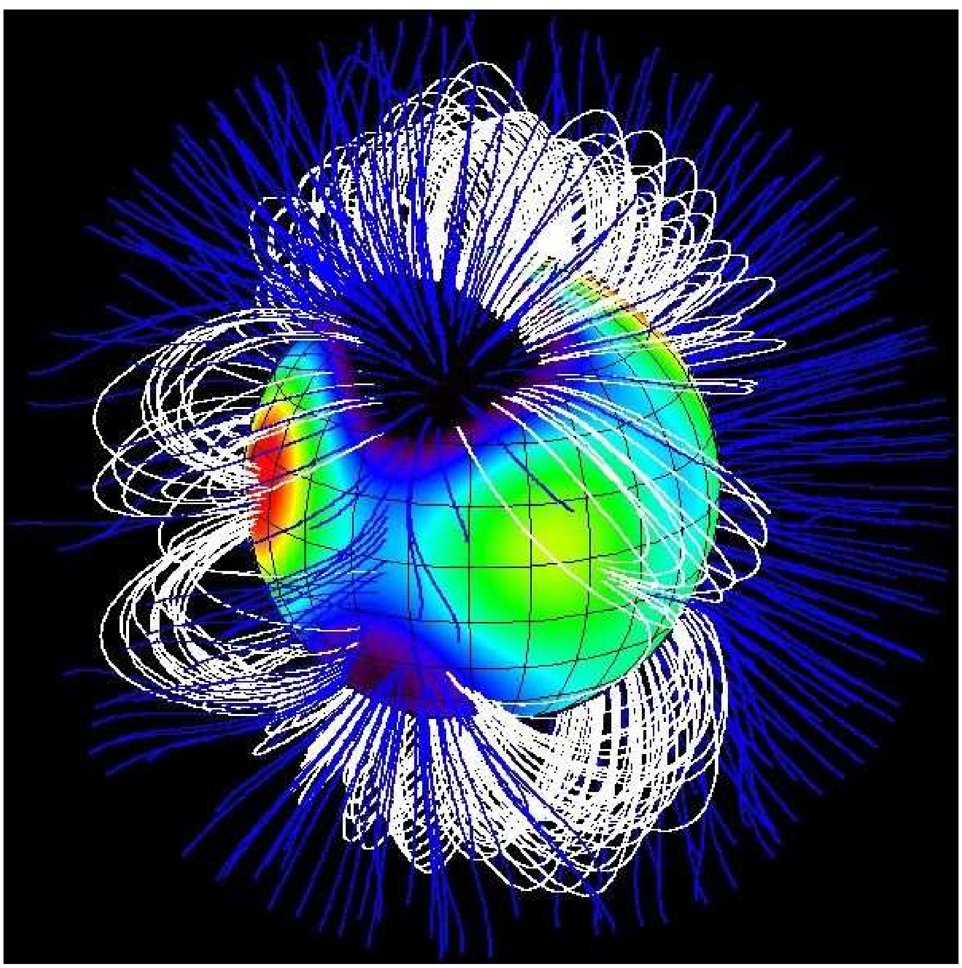

FIG. 2.— 3D representation of the magnetic field of τ Sco from the work of Jardine & Donati.

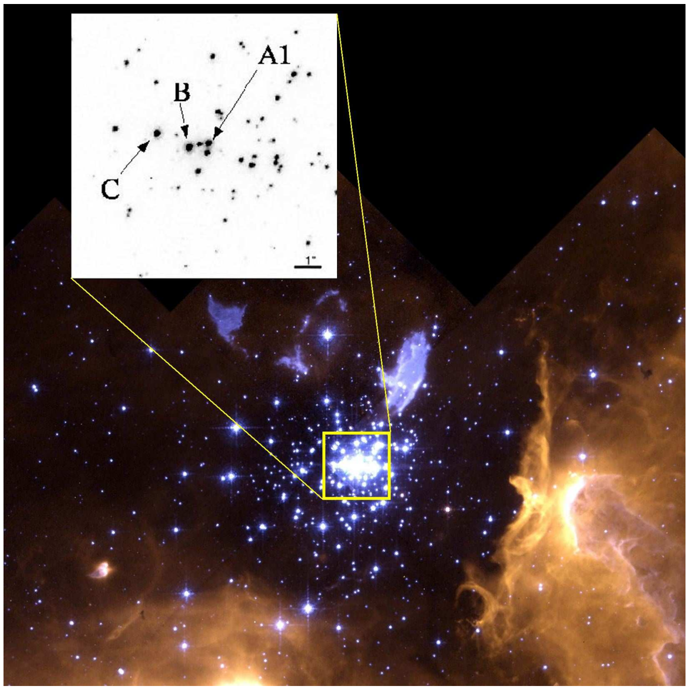

FIG. 3.— HST image of NGC 3603 including the three WN6ha stars at its very center

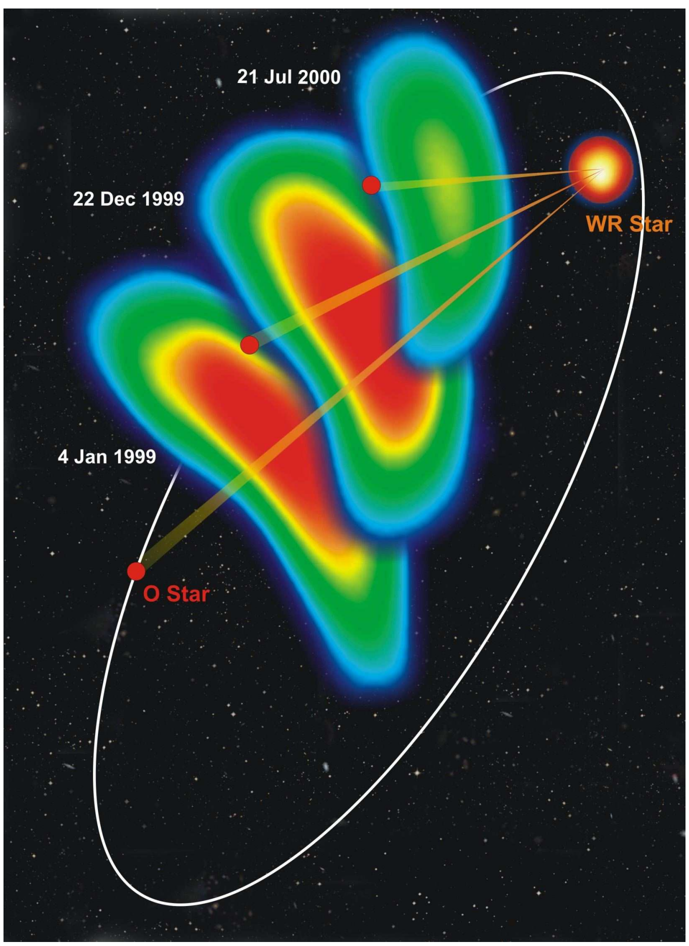

FIG. 4.— VLBA images of the non-thermal radio emission from the wind collision region in WR140 superimposed on the orbit (Dougherty et al. 2003). The actual size of the orbit is only a few mas.

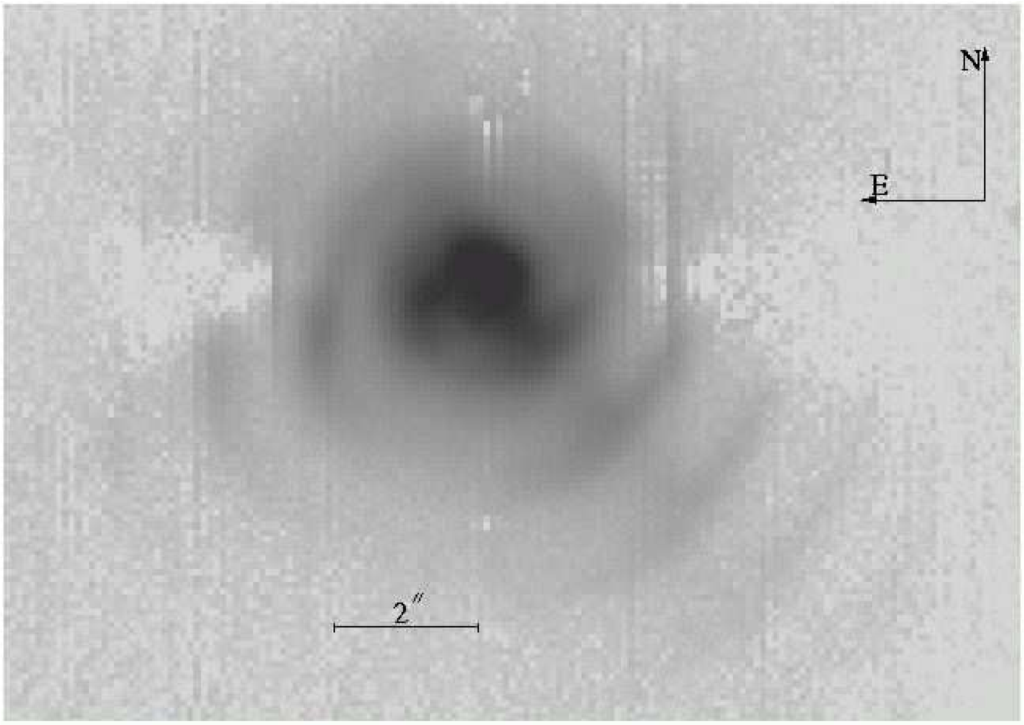

Fig. 5.— MIR image of the dust-forming WC9d star WR112 showing five cycles of a dust spiral.

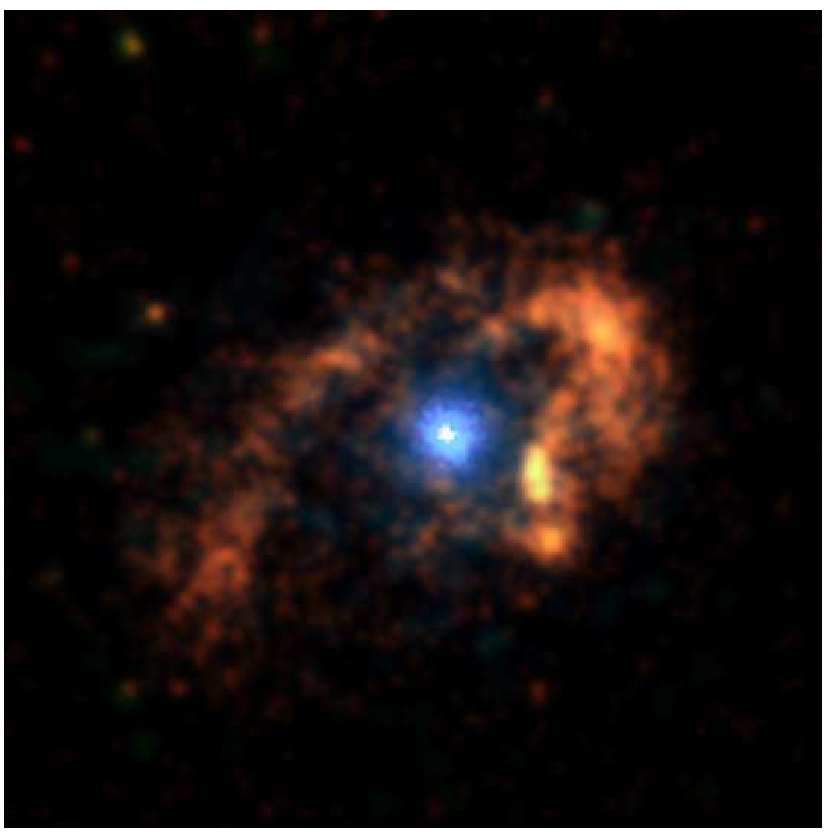

Fig. 6.— Chandra image of η Car showing hard X-rays coming from the unresolved colliding-wind region surrounded by softer X-ray emission from previously ejected material.

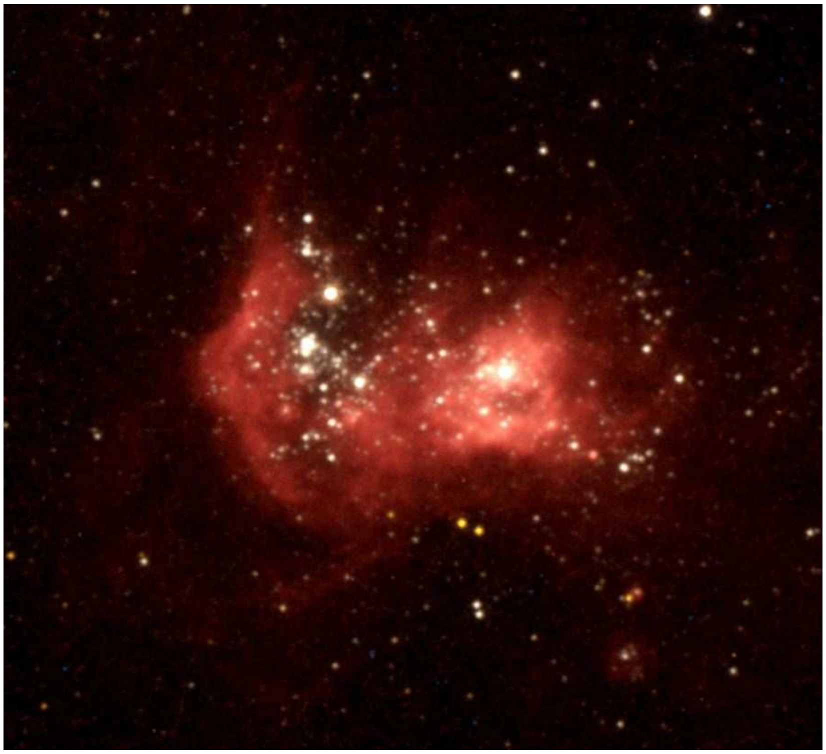

FIG. 7.— NGC 2363 is a giant HII region located at the end of the bar in the Magellanic galaxy NGC 2366 (D = 3.4 Mc). Rich of hundreds of OB stars and 3 WR stars, NGC 2363 is also host to a luminous blue variable, V1, which underwent a giant eruption in 1996.

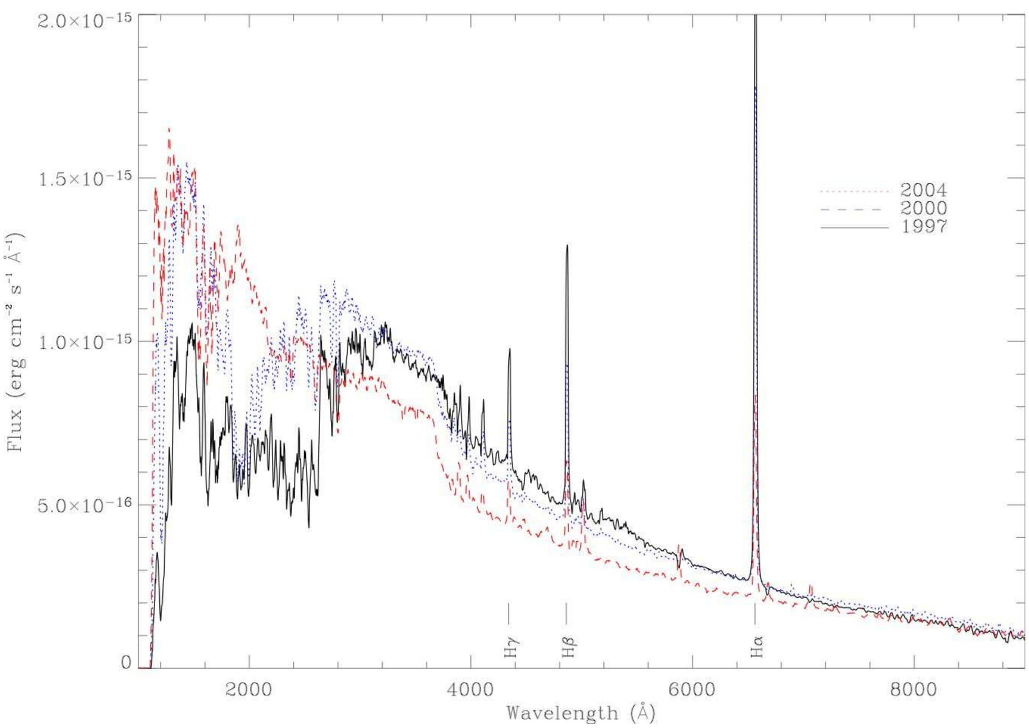

FIG. 8.— Spectroscopic evolution of NGC 2363-V1 from 1997 to 2004, showing the dramatic variability, especially in the ultraviolet. Data obtained with STIS onboard the Hubble Space telescope.