Top 10 Problems on Massive Stars

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(Organizers)

A foreword

Massive stars are rare and fascinating. While heavily obscured in the earliest stages of their lives, they evolve to become the brightest sources in their host galaxies when they die as supernovae. Their lifetimes are short, but the effects of massive stars in the galaxies are dramatic, altering their environments on both global and local scales.

Ten years ago, Dr. Andre Maeder compiled a list of 10 Most Topical Stellar Problems\(^1\) that became a reference for many astronomers, especially those new to the field. Since then, we have witnessed the birth of new ideas, and rapid improvement of theories and technologies that have had a profound impact on the field. We believe that it is time again to ask, what are the top 10 most interesting problems regarding massive stars?

To this end, we have asked a number of researchers in the field to compile their lists of the top 10 problems in the field of massive stars. This paper is a compilation of these lists. We attempted to survey observers and theorists and those studying all evolutionary stages in the lives of massive stars. Each list reflects the proposer’s personal point of view, but hopefully, this compilation will motivate new young astronomers and begin a new series of discussion.

\(^1\)Frontiers of Space and Ground-Based Astronomy: The Astrophysics of the 21st century, Dordrecht, Boston: Kluwer Academic Publishers, c1994, edited by W. Wamsteker, Malcolm. S. Longair, and Y. Kondo. Astrophysics and Space Science Library, Vol. 187, p.177)
Dr. Andre Maeder

1. In the formation of massive stars, what is the relative role of accretion and collisions?

2. How massive stars do form at metallicity Z\sim 0? What is the IMF, upper, lower mass limits and the fraction of binaries at Z\sim 0?

3. What are the distributions of rotational velocities at lower Z?

4. What is the role of magnetic field in formation and evolution of massive stars?

5. About the mass loss rates, what are they at different metallicities for all kinds of stars, OB stars, supergiants, WR stars?

6. What is the physics and role of internal mixing from MS to supernova explosions, for different masses and Z?

7. What is the exact role of binarity and mass transfer for the value of the chemical yields and the populations of massive stars?

8. What are the initial mass limits for the formation of neutron stars and black holes? How do these limits change with Z?

9. How to explain the rotation periods of young pulsars and the higher rotation necessary for the collapsar model?

10. Where is exactly the mass cut between what is ejected in supernova and what is captured in the remnants? How does it change with Z?
Dr. John Bally

1. ACCRETION OR MERGERS? Do massive stars form by direct accretion from a cloud or disk or by merging with other stars? Do both mechanisms operate? Which one dominates?

2. A FORMATION SEQUENCE: Is there an empirical evolutionary sequence for massive stars which is analogous to the Class 0, Class I, Class II, Class III sequence?

3. THE MASSES OF MASSIVE STARS: What determines the mass of a massive star? What determines the IMF in a massive cluster? What determines the upper-mass limit of massive stars? How does this mass limit depend on metallicity, stellar spin, and other environmental or intrinsic properties?

4. SUPERMASSIVE OBJECTS: What happens to a collapsing cloud that attempts to form a supermassive star?

5. THE FIRST STARS: What are the properties of zero-metallicity population III massive star forming regions? What is expected from theory? What can we observe?

6. STARS IN GALACTIC NUCLEI: How do massive stars form in galactic nuclei? How did the Sgr A cluster of massive stars form and evolve?

7. CONNECTIONS TO AGN: What are the relationship between massive star formation, super star cluster formation, globular cluster formation, and the birth of black holes, super-massive black holes, and the powering of AGN activity?

8. OUTFLOWS: How are protostellar outflows produced by massive stars produced? What processes are similar (different) to those in low-mass stars?

9. MAGNETIC FIELDS: What are the roles of magnetic fields in massive star formation?

10. MULTIPLES: How do massive star binaries and multiples form? Is the process similar to, or different from the formation of low-mass multiples?
Dr. Ed Churchwell

1. Do massive stars form primarily via accretion or by a combination of early accretion followed by mergers of low to intermediate mass protostars?

2. If by accretion then:
   
a) What is the mechanism that drives bipolar outflow?
   
b) What is the relationship between accretion, accretion disks, and bipolar outflows?
   
c) What is the role of gravity, radiation and stellar winds in protostars?

3. If by mergers then:
   
   a) What are the unique observational characteristics?
   
   b) How do we interpret the known massive outflows associated with some massive star formation regions?

4. Can we identify and understand the physical processes that determine the early evolutionary sequence of massive stars? Is the sequence: prestellar cores → hot cores → hypercompact HII s → ultracompact HII s → compact HII s and what changes occur with the central star through these phases?

5. Since most stars form as members of binary or multiple systems, this has to be included in any successful theory of star formation. Binary and multiple systems are natural consequences of the merger hypothesis but not so clear for the accretion hypothesis. Understanding the physics of multiple star system formation is a fundamental goal.

6. The distribution of stellar masses (i.e. the IMF) in young clusters appears to be essentially constant in the Galaxy despite formation in a wide range physical conditions (velocity fields, density, chemical composition, tidal forces, etc.). It is not understood what controls the IMF and until we do, we cannot claim that star formation is understood.
7. What is the role of magnetic fields in star formation? It is generally believed that star formation occurs by accretion and that magnetic fields somehow control the flow of matter into the associated bipolar outflows. However, only nature understands how this actually works.

8. Massive star formation occurs in highly obscured molecular clouds, so it has been very difficult to determine the stellar census of very young massive star formation regions. Deep MIR and NIR imaging and spectroscopic observations of these regions need to be obtained to reveal the location and relative numbers of stars that accompany the massive protostar that gives rise to hypercompact and ultracompact HII regions. Is the IMF in these very young regions the same as in older more evolved clusters?

9. Molecular line surveys of the Galaxy shows that the Milk Way has a prominent molecular ring with a galactocentric radius of \( \sim 5 \) kpc and a central bar. We know almost nothing about the stellar content and rate of star formation in these prominent components of our galaxy. This is a problem that needs serious attention.

10. What is the role of dust in the process of star formation? Is dust composition, size distribution, and charge critical to the process?

11. Is it possible for massive protostars to form planets? Are their accretion disks destroyed before planet formation can occur? Do the conditions in their accretion disks permit planet formation?

12. What is the origin of the mass in the outflows associated with massive protostars?

13. How did the first stars in the universe form in the absence of metal coolants? What were the properties of these stars?
Dr. Peter Conti

Stellar astrophysics involves the evolution of stars, their location, impact on their surroundings, and their role in the Universe.

Several of the most perplexing problems of the life of stars are concerned with their birth. There has been considerable progress over the past few decades in modeling their normal lifetimes and understanding the death processes, but the initial formation has typically been hidden from view by the presence of the natal clouds of dust and gas. As new wavelengths have opened to exploitation with improving telescopes and instrumentation we are finally beginning to be able to observe the birth itself.

1. Most OB stars form in clusters and associations from Giant Molecular Clouds but do all of them? Some stars are found well away from any known large stellar groupings. Have they escaped (the available time scale is short) or were they themselves merely the brightest members of otherwise rather skimpy small associations lower down on the molecular cloud IMF?

2. Does an individual star grow in mass from stellar accretion via a natal disc, or from mergers of smaller objects in a tight cluster environment? Could both of these processes play a role? Are there differences in the birth mode between single and close (or more distant) binary systems?

3. The terms “hot cores” and UCHII regions refer to some of the earliest stages of massive star birth. The former term refers to protostellar gas clouds that are already detectable from their thermal IR radiation; the latter term has to do with an ionized hydrogen region surrounding an already existing star hot enough to release prodigious amounts of Lyman continuum photons. Are the “hot cores” not quite hot enough (yet?) to generate UCHII regions or are they already doing so but their radiation is still buried within the natal clouds? Is there any distinction between hot cores and UCHII regions excited by close binaries or by single stars?

4. Most massive stars are born in giant molecular clouds. What is the effect of this dense stellar and gaseous dusty environment on the very early evolution of an individual object?

There has been dramatic improvement of our understanding of the evolution of massive stars during the last few decades. The following
unresolved issues come to mind:

5. What is the minimum mass above which a massive star will become a Wolf-Rayet type? How does this depend on the metallicity? In the close binary case, this number might well be lower, but by how much? It is even correct to talk about a minimum mass?

6. What is the minimum mass above which a massive star will end its life as a black hole, rather than as a neutron star? How does this depend on the metallicity, or the close binary nature? Is it even correct to talk about a minimum mass? Is this number related to the formation of W-R stars? Do all massive stars end their lives as supernovae or do some of them (the most massive?) turn directly into black holes?

7. What is the role of rotation and chemical mixing on the evolution of massive stars, both OB and W-R types? The importance of stellar winds in addressing this problem has been realized and its connection to rotation is in the beginning stages of solution. How do these physical processes couple? What role do close binaries play?

The location of massive stars in our Galaxy shows them to be closely confined to the galactic plane, so we are clearly in a spiral system.

8. What is the structure of the spiral arms? It is believed that we are in a multiple arm system given the longitude locations of OB stars near the sun. But does this carry around to sites beyond the galactic center, or are we being misled by the local view? How would our Galaxy appear optically (in the UV?) if viewed from well above (or below) the plane?

During their lifetimes massive stars eject ionizing photons, considerable wind energy, and processed nuclear material into their immediate environments. Their death as supernovae causes another spike of energy and a substantial ejection of “heavy” elements into the interstellar medium.

9. How does the importance of these processes depend on the initial metallicity? What role do close binaries play in modifying these events?

As we inquire into how the Universe has evolved, we realize that “In the beginning” there were massive stars. Much larger telescopes and greatly improved instrumentation are now beginning to probe the very
youngest galaxies and their constituent stars. These will be predominantly the OB types (although that classification will need to be modified in the no “metals” case).

10. How do massive stars evolve in the limit of no “metals” during the earliest stages of the evolution of the Universe? Modeling using both rotation and stellar winds will need to be made. Do either of these processes play a role in causing internal mixing and could that process modify how an individual first generation massive star evolves?
Dr Philippe Eenens

Here are a few questions which puzzle me:

1. Massive star birth;
2. Wind velocity law of WR stars;
3. Departure of WR stars from spherical winds;
4. Rotation rates of WR stars;
5. Evolutionary links between B[e], LBV and WR stars;
6. Presence of dust in hot winds;
7. Evolution of WR into supernova;
Dr. Neil Evans II

1. Primordial Star Formation, with only H$_2$ as a coolant.

2. How much metallicity is needed before the nature of star formation changes enough to permit a fuller range of masses?

3. What drives starbursts in high-z galaxies and what are properties of the stars (IMFs, etc.)?

4. How similar are the conditions in dusty starbursts to those in massive star forming regions in our Galaxy?

5. What controls the IMF in current (Galactic) star formation?

6. Can we actually see the fragmentation in massive dense cores in an unbiased tracer?

7. What chemical changes go on and how do they affect observed line profiles?

8. How are the dust properties changing during massive star formation, and how do those changes affect observed emission from dust?

9. Can we trace the dynamical process of collapse and fragmentation with any molecular line tracer?

10. What are the feedback effects of massive stars on the formation of other stars?
Dr. Henny Lamers

In my order of priority:

1. How do massive stars form?
   Co-agulation requires very fine-tuning of the conditions and time scales.
   I am doubtful that it will work.

2. What causes the high mass loss rates of WR stars?
   The present radiation driven wind models start at the photosphere,
   but there must be a very deep subsonic moving (!) region between the
   hydrostatic core (about $1 \, R_\odot$) to the photosphere (about $10 - 20 \, R_\odot$).
   The mass loss rate is determined somewhere deep down, possibly just
   above the hydrostatic core. (ps: Nugis and Lamers are trying to model
   this)

3. How does the mass loss rate vary with metallicity at low metallicities?
   This is important for the evolution of the first generation stars.

4. What causes the outbursts of LBVs?
   They are close to their Eddington limit, even deep inside the star so
   they are probably marginally stable. Any internal disturbance might
   have a large effect. But what is this disturbance? What sets the time
   scale?

5. What is the role of rotation of massive stars?
   The final fate will depend crucially on the rotation and on the transport
   of angular momentum. (I have tried to derive this observationally by
   studying the abundances of WR and LBV nebulae, and conclude that
   rotation induced mixing must occur on a timescale that is several times
   the MS-lifetime (Lamers, Nota, Panagia, et al. ApJ few years ago).

6. Do all massive stars form in clusters?
   In our galaxy: probably yes. But there may be special environments
   where this is not the case. e.g. near the core of M51 (Lamers et al,
   2003,ApJ) Are there other cases where this happens?

7. What sets the upper mass limit for star formation?
I always thought that is is the Eddington limit, but Norbert Langer tells me that is not the case. A very massive star can survive by becoming convective and thus reducing the radiative flux and the radiation pressure (this also happens in very luminous WR stars). This question may be related to point 1 (formation)

8. Is the IMF for massive stars the same everywhere? (related to 1 and 7)
Dr. Norbert Langer

1. How do the most massive stars form? Which are the highest masses made? Does the formation process depend on metallicity or environment?

2. How do massive stars explode when they form a neutron star? Does the "prompt explosion mechanism" apply to the lowest mass iron cores; perhaps in close binaries? Is it the neutrinos that are responsible for most supernovae in the "delayed explosion mechanism"? What produces the neutron star kicks?

3. Do massive stars explode when they form a black hole? Which fraction of them creates gamma-ray bursts, which hypernovae? Is there a specific role for massive stars in close binaries? Do black holes receive a kick when they are born?

4. What is the role of magnetic fields in the interior of massive stars? Are the torques exerted by them strong enough to slow down the core so that we can understand the spin rates of young pulsars? But if so, how do we get the rapidly rotating cores required for the collapsar model of gamma-ray bursts?

5. Which is the site of the r-process. Massive stars, for sure but which and where? And how many r-process components exist?

6. In a mass transferring massive binary, which fraction of the overflowing matter can be retained by the mass receiving star? This question is relevant to all post-mass transfer binaries: massive Algols, Wolf-Rayet binaries, X-ray binaries, double-neutron star binaries, Type Ib/c supernovae, gamma-ray bursts (long and short),... It is also strongly connected to the star formation process: if disk accretion is involved, it may work the same way in newly born stars as in "rejuvenated" ones in close binaries.

7. What drives red supergiant mass loss? How big are the mass loss rates? How does the mass loss rate depend on metallicity, or envelope chemical composition?
8. What causes LBV giant eruptions? Why are all LBV nebulae bipolar? What is the metallicity dependence of the LBV eruptions? I.e., at very low metallicity, do the most massive single stars go through an LBV stage, thereby lose most of their envelope form Wolf-Rayet stars? If not, there may be no other way to for WR stars, with two consequences: single stars could not form gamma-ray bursts from collapsars, and stars above 60...100 solar masses would not form iron cores but explode as pair creation supernovae during oxygen burning.

9. What is the origin of the Ultraluminous X-ray Sources? Are there black holes of 100 Msun and more in binary systems? Is there a continuous mass spectrum of black holes, from stellar (2...15 M☉) to supermassive (...10⁸ M☉) ones?

10. How do supernova ejecta merge with the interstellar medium? What is the role in this of the pre-supernova shaping of the circumstellar medium from the supernova progenitor’s winds and photons? What is the role of supernovae for star formation? How do the hot ejecta mix with molecular clouds? Which are particles are accelerated to form the cosmic rays?
Dr. Anthony Moffat

1. Need for a self-consistent, complete model of massive-star evolution (e.g. without having to assume a beta-law for the wind!)

2. What is the birth scenario of massive stars?

3. What is the upper mass-limit of star formation?

4. Is the IMF the same for single stars as those in binaries?

5. What is the initial binary frequency; does it vary with Z, mass, ...?

6. Under what conditions does RLOF take place and how is it important?

7. What is the mechanism behind LBV eruptions?

8. What happens at Z = 0 (pop III), where all stars are probably massive?

9. How does dust form?

10. Do massive stars produce GRBs (short ones from merging of NS/NS or NS/BH, long ones from collapsing rapid rotators?)?

11. Do WR stars explode as SN Ib/c?

12. What is the structure of WR winds in the optically thick zone and what are the true hydrostatic radii?

13. Are all stars formed in clusters/groups; origin of isolated OB/WR stars?
Dr. Jonathan Tan

1. What are the lifetimes and formation mechanisms of Giant Molecular Clouds (GMCs), the hosts of all present-day massive star formation? (i.e. how long do they exist as coherent structures before being dispersed, how does this compare with the timescale for the dissipation of their turbulence, and how important is continued energy injection from internal star formation or external perturbations?)

Observationally, the mass fraction of a galaxy’s interstellar medium (ISM) that is associated with GMCs (and associated atomic halos) approximately tells us the relative amount of time gas spends in bound and unbound states. Together with other data, e.g. cloud angular momenta, this helps constrain formation scenarios. On the theoretical side, numerical simulations of magneto-hydro-dynamic turbulence indicate short decay times of just a few million years, but it is not yet clear if these models capture all the physics of real clouds.

2. What, if any, is/are the triggers for star cluster formation from highly localized regions of GMCs, and how does this answer relate to trends in total galactic-scale star formation, such as the Schmidt-Kennicutt relations?

This question will probably be answered observationally via a study of the regions that are precursors to those of active massive star formation. These are best identified via mid-infrared absorption (e.g. the dark clouds seen by the ISO and MSX satellites). Then an association with spiral arms, cloud collisions, supernova remnants, etc. can be searched for.

3. Does massive star formation (or indeed any kind of star formation in star clusters) proceed in a manner best modeled as the collapse of quasi-equilibrium structures (“cores”) or as competitive Bondi-Hoyle accretion?

Apparently coherent, equilibrium cores are commonly observed, with a mass function that is apparently quite similar to the stellar initial mass function (IMF). These observational studies need to be extended to the more distant and denser regions characteristic of high-mass star formation. Reconciling the simulations of a turbulent ISM with the apparent existence of equilibrium cores is an important goal.
4. What sets the shape and upper limit of the stellar IMF, and does this vary for different initial conditions of the interstellar medium?

There appears to be a physical process that limits the mass of Galactic stars (the IMF appears to be a power law truncated above about $\sim 100 - 200 M_\odot$), but it is not known whether this is due to the action of feedback during the formation process, is due to dynamical processes in the forming star clusters, or is due to some instability in the structure of very massive stars that initiates rapid mass loss. The power law shape may be already present in cores (see Q3) or may result independently. Massive star formation is observed to occur in a wide range of conditions, such as dense clumps inside GMCs, the high pressure environment of our Galactic center, and in massive, relatively low-metallicity clouds in dwarf galaxies such as the Large Magellanic Cloud, and it is important to continue looking for variations in the IMF from region to region. Surprisingly no differences have been found in such studies. Within individual protoclusters there is tentative evidence that massive stars are biased to the more central regions: more observations, coupled with detailed n-body modeling of specific clusters are needed to confirm this.

5. Are there disks around massive protostars, and, if so, how do their properties (size, mass, etc.) compare to those around lower mass stars?

There have been several interesting observational claims for massive protostellar disks, but so far none (in my opinion) are completely unambiguous. Another question is if disks are present, then do they maintain their orientation over many dynamical timescales - i.e. is their orientation set by overall angular momentum of a coherent core surrounding and feeding the disk - or does the orientation change because the feeding is more erratic?

6. What determines the nature of massive star binaries? Do planets form around massive stars?

Answering this question can help lead to a better understanding of the star formation mechanism: do binaries and/or planetary companions form from a common disk inside a core, by chance dynamical interactions in a crowded star cluster, or by a combination of both mechanisms? As observational techniques to find planets improve, it may
become possible to look at planet frequency over a wide range of stellar masses, as has been done for protostellar disks in young star clusters.

7. How are runaway OB stars created?

Again observational studies of individual systems are the best hope for answering this question, with the leading theories being from three body interactions in young star clusters, or from the supernova explosion of a massive star with a massive companion.

8. What is the nature of outflows from massive protostars - in particular, are they driven magnetocentrifugally (via disk winds or X-winds) as is thought to be the case with low-mass protostellar outflows, or does radiation pressure star to become more important?

Outflows around massive protostars may well confine hypercompact HII regions, and VLBA studies of these sources (e.g. source “I” in Orion) can help determine the properties of the outflow on scales of tens of AU. Maser observations can also help determine the outflow properties, although there remains the caveat of the precise relationship between observed maser spot velocity and true flow velocity. Outflows from massive protostars should initially have speeds of order 1000 km/s.

9. What feedback processes, if any, determine the efficiency of star formation from both individual cores or protoclusters?

This is a very complicated problem, and for the moment is beyond an accurate numerical study. Simple analytic and semi-analytic models may give some guidance, but only if they are tied closely to observations of young and forming star clusters.

10. How does including rotation affect protostellar structure and evolution models?

By determining the size of the star, protostellar structure affects the stellar luminosity and the strength of outflows from the inner accretion disk. Stellar evolution models including rotation are now available, and these need to be extended to include the protostellar phase.
Dr. Nolan Walborn  
My Top (Ten) Eleven! Problems on Massive Stars

1. What are the physical parameters and generic relationships of the several classes of optically observable, very young (near or on ZAMS) massive stars? Several categories and phenomena (not always in the same objects) have been described, but there has been little or no directed, systematic, quantitative analysis of them. They include objects in dense nebular knots, with excessively strong Balmer lines (class Vb) or He II 4686 stronger than other He II lines (class Vz, inverse Of effect?), with weak UV wind profiles for their types, and subluminous (fainter than class V) objects.

2. What are the true distances and luminosities of OB stars in the solar neighborhood? This question will be answered only by SIM and GAIA.

3. Which OB stars in the solar neighborhood and the Magellanic Clouds are single objects and which are unresolved multiple systems? With current instrumentation, there is an unobservable gap between the spectroscopic-binary limit of 1 AU and the interferometric imaging limits of, e.g., 25 AU in the Carina Nebula or 500 AU in the LMC (for components of similar brightness).

4. What are the true masses and the upper mass limit of OB stars? Progress is being made, but we need to have a definitive temperature scale and resolution of systematic differences between different methods of determining masses (spectroscopic/eclipsing binaries, atmospheric spectral analysis, evolutionary models).

5. Do the statistics of CNO line strengths in OB supergiants (OBC vs. morphologically normal vs. OBN classes) correspond to those of initial main-sequence rotational velocities? Are there systematic rotational differences corresponding to relative surface CNO differences among different clusters?

6. Are the winds of normal OB and WR stars spherically symmetric or not? What is the physics of WR winds?

7. What are the physical parameters and generic relationships of the many varieties of luminous, evolved, emission-line OB stars, i.e. the OB Zoo?
They include the following categories: WN-A (WN6-8L), O Iafpe and Ofpe/WN9 (WN9-10ha), B Iape (WN11h), Iron (Fe II), and LBV. Some relationships have been established, e.g. Ofpe/WN9 and B Iape spectra have been observed in the minimum state of certain LBVs, but the global relationships are far from clear, and may well be functions of mass and metallicity.

8. Which of the foregoing and other phenomena correspond to evolutionary states of single massive stars, and which arise from close-binary interactions? Starting with Eta Carinae!

9. What are the OB progenitors of the multiplying varieties of core-collapse SN? And of GRB?

10. Have we identified and correctly modeled the fundamental parameters that determine massive stellar evolution in detail? At the highest level, they are now believed to be mass, metallicity, and initial rotational velocity. Are magnetic fields a significant variable or not? What are the evolutionary tracks and sequences of spectral states corresponding to all relevant combinations of these parameters?

11. And finally, we ultimately need physical models that reproduce observed spectra and luminosities from first principles! Current models are replete with ad hoc parameters (e.g., convection, mixing, mass-loss rates) that are adjusted to apparently match observations, but there is no guarantee that such procedures are unique or correspond to real phenomena in nature.
Dr. Stan Woolsey

Eight top issues:

1. How do massive stars die?
   After 50 years of research we still don’t know. Do rotation and magnetic fields play a role or can neutrinos alone make a succesful supernova explosion? Even the non-rotating, non-magnetic calculations strain current codes and resources beyond credibility.
   The location of the mass cut influences the composition of the universe, which SN make black holes and which make neutron stars, and the nature of GRBs.

2. What is the evolution of angular momentum inside massive stars?
   If the star rotates rigidly on the ZAMS, what is the j of the final collapsed remnant? How does rotational mixing affect the evolution and the abundances seen at the surface?

3. What is the mass loss rate as a function of metallicity, mass, and evolutionary stage
   What is the mass of the star when it dies and how does mass loss affect nucleosynthesis? What are the mass loss rates of WR stars of various mass and initial metallicities?

4. How are massive stars formed?
   Is their birth fundamentally different from low mass stars. What is the metallicity dependence of the star formation process and a related questi

5. How has the IMF evolved with metallicity in the universe. What were the masses of typical stars with $Z = 0$? What was the heaviest star made? What its mass when it died?

6. How to treat convectiive boundaries and semiconvective regions
   What is the overshoot length as a function of e.g., the pressure scale height or the entropy contrast? What is the semiconvective diffusion coefficient?
7. How has membership in binaries affected the evolution and the properties of the star at death?

8. What nucleosynthesis has each massive star of a given Z and mass contributed?