

IAU Symposium 250
Massive Stars as Cosmic Engines

INVITED REVIEWS AND CONTRIBUTED TALKS
(in order of presentation)

MONDAY, 10 December 2007

SESSION I: Atmospheres of Massive Stars

Massive Stars as Cosmic Engines through the Ages

REVIEW

André Maeder, Geneva Observatory

The evolution and properties of massive stars at different Z , from the first stars to the present-day populations are reviewed with emphasis on the filiations, number of different stars, chemical abundances, and yields. The interplay of rotation, mass loss with anisotropic winds, and magnetic fields is a key aspect, also for the nature of the progenitors of GRBs. Signatures of enrichments by the winds of early generations of massive stars are visible in halo stars and in globular clusters. We also point out the occurrence of thick convective envelopes in massive rotating stars and their consequences.

X-ray Emission from O Stars

David Cohen, Swarthmore College

Young O stars are strong, hard, and variable X-ray sources, which strongly affect their circumstellar and galactic environments. After <1 Myr, these stars settle down to become steady sources of soft X-rays. I will use high-resolution X-ray spectroscopy and MHD modeling to show that young O stars like θ^1 Ori C are well explained by the magnetically channeled wind shock scenario. After their magnetic fields dissipate, older O stars produce X-rays via shock-heating in their unstable stellar winds. Here too I will use X-ray spectroscopy and numerical modeling to confirm this scenario. In addition to elucidating the cause and nature of O star X-ray emission, modeling of the high-resolution X-ray spectra of O supergiants provides strong evidence that mass-loss rates in these stars have been overestimated.

Physical and Wind Properties of OB Stars

REVIEW

Joachim Puls, University Observatory Munich

In this review, we will summarize major achievements and findings since the last massive star symposium in 2002. After a brief comparison of present state-of-the-art atmospheric models, we will discuss the latest spectral-type/ T_{eff} calibrations for OB stars, in dependence of metallicity. Important results from the VLT-FLAMES survey of massive stars in the Galaxy and the Magellanic Clouds are presented, in particular regarding rotation and nitrogen enrichment and their implications for massive star evolution. We will comment on the present state of the “mass discrepancy,” the presence of magnetic fields, and the puzzle of supersonic “macro-turbulence” observed in a large number of massive stars.

With respect to their radiation-driven winds, we will concentrate on recent findings regarding the wind-momentum–luminosity relation, the problem of clumping and the so-called “weak wind problem.” Finally, we will give some comments on the revival of an old debate in radiation-driven wind theory, namely on the question of the critical point.

The Metallicity Dependence of the Mass-Loss Rate of Early-Type Massive Stars

Alex de Koter, Astronomical Institute “Anton Pannekoek,” University of Amsterdam

The FLAMES Survey of Massive Stars (Evans et al. 2005) has observed a large sample of O- and B-type stars in clusters in the Galaxy and the Magellanic Clouds to fully investigate the role of metallicity and rotation on stellar evolution. As part of this program, we have derived the mass-loss rates of our 100 O and early-B stars in these galaxies using a newly developed automated spectral analysis method. The size of this sample and the homogeneous analysis method allow for a robust determination of the dependence of mass loss on surface metal content. I will present this empirical $dM/dt(Z)$ relation in the metallicity range spanned by these galaxies and confront it with theoretical predictions.

Properties of Wolf-Rayet Stars

REVIEW

Paul Crowther, University of Sheffield

I shall review various aspects of recent progress relating to Wolf-Rayet (WR) stars, including improved statistics (e.g., IR surveys), binarity, definitions of hydrogen-rich WN stars versus Of supergiants, spectroscopic analysis of WR stars resulting in temperatures, luminosities, abundances, ionizing fluxes, and wind properties, plus the impact of winds upon WR subtype distributions resulting from metallicity-dependent winds.

Wolf-Rayet Wind Models from Hydrodynamic Model Atmospheres

Götz Gräfener & Wolf-Rainer Hamann, Universität Potsdam

We present a parameter study of WR-type mass loss, based on the PoWR hydrodynamic model atmospheres. These new models imply that optically thick WR-type winds are generally formed close to the Eddington limit. This is demonstrated for the case of hydrogen-rich WNL stars, which turn out to be extremely massive, luminous stars with progenitor masses above $\approx 80 M_{\odot}$. We investigate the influence of WR-type mass loss on various stellar parameters, including the metallicity Z . The results depend strongly on the L/M ratio, the stellar temperature T_{\star} , and the assumed wind clumping. For high L/M ratios, strong WR-type winds can be maintained down to very low Z . Even for primordial massive stars, we predict considerable mass loss if their surfaces are self-enriched by primary elements.

Luminous Blue Variables and Mass Loss near the Eddington Limit

REVIEW

Stan Owocki & Allard-Jan van Marle, Bartol Research Institute, University of Delaware; Nir Shaviv, Racah Institute of Physics, Hebrew University

During the course of their evolution, massive stars lose a substantial fraction of their initial mass, both through steady winds and through relatively brief eruptions during their luminous blue variable (LBV) phase. This talk reviews the dynamical driving of this mass loss, contrasting the line-driving of steady winds to the potential role of continuum driving for eruptions during LBV episodes, when the star exceeds the Eddington limit. A key theme is to emphasize the inherent limits that self-shadowing places on line-driven mass-loss rates, whereas continuum driving can in principle drive mass up to the “photon-tiring” limit, for which the energy to lift the wind becomes equal to the stellar luminosity. I review how the “porosity” of a highly clumped atmosphere can regulate continuum mass loss, but also discuss recent time-dependent simulations of how base mass flux that exceeds the tiring limit can lead to flow stagnation and a complex, time-dependent combination of inflow and outflow regions. I conclude with a brief discussion of interior processes that could trigger the super-Eddington luminosity of LBV eruptions.

Pulsation-Initiated Mass Loss in Luminous Blue Variable Stars: A Parameter Study

Andrew J. Onifer & Joyce A. Guzik, Los Alamos National Laboratory

Luminous blue variables (LBVs) are characterized by semi-periodic episodes of outburst. The cause of these outbursts has thus far been a mystery. One possible explanation is that they are initiated by pulsations in the atmosphere caused by a buildup of luminosity at temperatures near the so-called “iron bump” ($\sim 200,000$ K). Due to a lag in the onset of convection, this luminosity can build until it exceeds the Eddington limit locally, driving some mass from the star. I present results from a parameter study focusing on the conditions necessary to trigger normal (as opposed to extreme) outbursts. The implications for mass loss will also be discussed.

What Do We Really Know about O Star Winds?

D. John Hillier, University of Pittsburgh

The standard theory of radiation driven winds has provided a useful framework to understand stellar winds arising from massive stars (O stars, Wolf-Rayet stars, and luminous blue variables). However, with new diagnostics, and advances in spectral modeling, deficiencies in our understanding of stellar winds have been thrust to the forefront of our research efforts. Spectroscopic observations and analyses have shown the importance of inhomogeneities in stellar winds, and revealed that there are fundamental discrepancies between predicted and theoretical mass-loss rates. For late O stars, spectroscopic analyses indicate mass-loss rates significantly lower (order of magnitude) than predicted. For all O stars, observed X-ray fluxes are difficult to reproduce using standard shock theory, while observed X-ray profiles indicate lower mass-loss rates, the potential importance of porosity effects, and an origin surprisingly close to the stellar photosphere. We discuss these various issues and suggest possible solutions.

The Physical Properties of Red Supergiants

REVIEW

Philip Massey, Lowell Observatory; Emily M. Levesque, Institute for Astronomy, University of Hawai'i; Bertrand Plez, GRAAL, Université de Montpellier II, CNRS, et al.

Red supergiants (RSGs) are an evolved stage in the life of intermediate massive stars ($<25 M_{\odot}$). For many years, their location in the H-R diagram was at variance with the evolutionary models. Using the MARCS stellar atmospheres, we have determined new effective temperatures and bolometric luminosities for RSGs in the Milky Way, LMC, and SMC, and our work has resulted in much better agreement with the evolutionary models. We have also found evidence of significant visual extinction due to circumstellar dust. Although in the Milky Way the RSGs contribute only a small fraction ($<1\%$) of the dust to the interstellar medium (ISM), in starburst galaxies or galaxies at large look-back times, we expect that RSGs may be the main dust source. We are in the process of extending this work now to RSGs of higher and lower metallicities using the galaxies M31 and WLM.

The Evolutionary State of the Cool Hypergiants

Roberta Humphreys, University of Minnesota

The evolved cool stars near the empirical upper luminosity boundary in the H-R diagram all show evidence for considerable instability perhaps due to their proximity to this stability limit and/or their evolutionary state. Recent high-resolution imaging and spectroscopy of several of these stars have revealed a subset characterized by complex ejecta and evidence for episodic mass loss driven by convective activity and magnetic fields. This group includes famous stars such as the red supergiants VY CMa, NML Cyg, and the post-RSG IRC +10420. I will review the observational evidence and discuss the implications for the final stages of these evolved stars, their mass loss mechanism, and evolutionary state.

Massive Binaries

REVIEW

Anthony F. J. Moffat, Université de Montréal

As with all binaries, those that contain massive stars reveal various degrees of interaction, depending mainly on orbital separation and age, although things happen much faster in massive binaries. Those massive binaries with initial periods exceeding several years generally only interact via wind-wind collisions, with little or no effect on their evolution (unless located in dense clusters). Shorter-period systems show even stronger wind-wind collisions as a rule, but also interact more directly via Roche-lobe overflow or common envelope, with dramatic effects on their evolution. If we didn't have such strongly interacting massive binaries, the Universe would be missing a whole host of interesting phenomena, such as non-thermal radio or enhanced stellar X-ray emission, WR dust-spirals, very rapid spin, massive blue-stragglers, many runaways and possibly even SMBHs and GRBs! On the other hand, non- (or little) interacting massive binaries are also useful to provide information on star formation processes and determination of stellar parameters that would otherwise be difficult or impossible to obtain from single stars. In this review, I will highlight some of the developments that have occurred in this area during the past few years since the last IAU symposium on massive stars in 2002.

3-D SPH Simulations of Colliding Winds in η Carinae

Atsuo Okazaki, Faculty of Engineering, Hokkai-Gakuen University

We report on the results from three-dimensional, smoothed particle hydrodynamics (SPH) simulations of colliding winds in the supermassive binary η Carinae. For simplicity, we take both winds to be isothermal and coasting without any net external forces, assuming that gravitational forces are effectively cancelled by radiative driving terms. We find that the low-density, high-velocity wind from star B makes a spiral cavity in the high-density, low-velocity wind from star A. The cavity is transient on the periastron side, leaving only a narrow wake, whereas it dominates the wind from star A on the apastron side, finally occupying most of the volume. Our simulations suggest that the observers are not on the periastron side but on the apastron side of η Car.

TUESDAY, 11 December 2007
SESSION II: Physics and Evolution of Massive Stars

Developments in the Physics of Massive Stars

REVIEW

Georges Meynet, André Maeder, & Raphael Hirschi, Geneva Observatory, et al.

We shall present the effects of various mass-loss-rate prescriptions, the consequences of rotational mixing and of the Tayler-Spruit dynamo on the structure and the evolution of massive stars. The metallicity dependence of the above effects implies that the evolution of the high-metallicity massive stars is mainly affected by mass loss, while the metal-poor ones have their evolution strongly modified by rotational mixing and mass loss. Interesting consequences for stellar populations in galaxies, chemical evolution, Pop III stars, and gamma-ray burst progenitors will be discussed.

Can Pulsational Instabilities Impact a Massive Star's Rotational Evolution?

Richard Townsend, Bartol Research Institute, University of Delaware

During their evolution off the main sequence, massive stars are subject to global instabilities that excite a variety of pulsation modes. These modes can be very efficient both at transporting angular momentum from one region of a star to another, and at triggering additional mixing. In this talk, I'll present results from an initial investigation into these effects, examining whether they can have a significant impact on stellar evolution.

Close Binary Evolution

REVIEW

Norbert Langer, Utrecht University

I focus on the early evolution of massive close binary systems: how well understood is the pre-mass transfer evolution, and the evolution during and after the first mass transfer. I explain why massive binary evolution needs to be understood in order to constrain the physics which is relevant for massive single stars, in particular overshooting, rotational mixing, and magnetic field effects. I point out the significance of the $v_{\text{rot}} \cdot \sin i$ versus surface nitrogen-diagram ("Hunter-diagram"), as derived from the ESO FLAMES survey for a new understanding of massive single and binary stars.

The Effect of Massive Binaries on Stellar Populations and Supernova Progenitors

John J. Eldridge, Institute of Astronomy, University of Cambridge; Robert G. Izzard, Sterrekundig Instituut Utrecht, Utrecht University; Christopher A. Tout, Institute of Astronomy, University of Cambridge

First, we outline how we have calculated a large set of detailed binary models and compared them to the observed relative populations of blue supergiants, red supergiants, and Wolf-Rayet stars at different metallicities. We have also compared our models to the relative rate of type Ib/c to type II supernovae. We find better agreement between our models and observations by considering binary stars rather than just single stars alone. We will then discuss the use of our models in determining the nature of supernova progenitors, showing the surprising result that many type Ib/c supernova progenitors are less luminous and less massive than current models predict.

Theories of the Explosive Death of Massive Stars

REVIEW

Adam Burrows, University of Arizona

Modern supernova simulations suggest that one or more of three general classes of explosion mechanisms are employed by Nature to end the life of a massive star. These are the neutrino, acoustic, and MHD mechanisms. However, though the computer codes currently applied to this puzzle incorporate the requisite physics with increasing fidelity, they are not yet able to settle the question. Moreover, it is now clear that the gamma-ray burst phenomenon and the supernova phenomenon are related, however distantly. I will present results of various simulations, the physics behind them, and predictions concerning the gravitational-wave, neutrino, and pulsar signatures of various scenarios. The goal is to summarize where theory is and where theory is going.

Episodic Mass Loss and Pre-Supernova Circumstellar Envelopes

Nathan Smith, University of California, Berkeley

I will discuss various observational clues concerning episodic mass-loss properties of massive stars in the time before the final SN explosion. In particular, I will focus on the mounting evidence that LBVs and related stars are candidates for SN progenitors, even though current paradigms suggest that they are only supposed to be at the end of core-H burning, plus potential solutions to this problem. Finally, I will highlight evidence from observations of some recent extraordinary supernovae suggesting that explosive or episodic mass loss (a.k.a. LBV eruptions, like the nineteenth century eruption of η Car) occurs in the 5–10 years immediately preceding the SN.

The Progenitor Stars of Core-Collapse Supernovae

Stephen Smartt, Queen’s University Belfast

The HST archive is a rich source of deep and multi-colour images of galaxies in the nearby Universe, and this legacy will be useful for decades to come. These images resolve much of the massive stellar populations, and most of the large late-type spirals within 20 Mpc have been observed. When a core-collapse supernova explodes in these galaxies, we can attempt direct detection of the progenitor star. During Cycles 10–15, we have had ToO status on HST to directly detect the massive progenitor stars of nearby supernovae in archive images. We have detected the progenitors of six type II-P showing them to be red supergiants with initial masses close to the theoretical limit for core-collapse ($8 M_{\odot}$). We have set robust upper luminosity and mass limits on another 12 progenitor stars (from type II-P, and Ib/c) supernovae. I will review the results from our work, and others in the field, that is constraining stellar evolutionary theory and limiting SN explosion models. It appears that faint SNe, which have been thought to come from black-hole forming SNe, are more likely to have low-mass progenitors. I will present direct constraints on the progenitors of type Ib/c SNe which are related to gamma-ray bursts.

Magnetars and Their Massive Star Progenitors

REVIEW

Bryan M. Gaensler, The University of Sydney

Magnetars are a small group of young neutron stars powered by extreme magnetic fields, with surface strengths in excess of 10^{15} gauss. Now that magnetars have been established as a significant fraction of the overall neutron star population, we need to understand why some core-collapse supernovae make “normal” radio pulsars, while other supernovae make exotic magnetars. I will review a series of recent multi-wavelength results on the environments and birth-sites of magnetars, which as an ensemble provide strong evidence that magnetars originate from unusually massive stars. I will discuss the resultant implications for the formation and birthrate of magnetars, for the magnetic fields of high-mass stars, and for the rate of long gamma-ray bursts in high-metallicity galaxies.

Can Very Massive Stars Avoid Pair-Instability Supernovae?

Sylvia Ekström, Georges Meynet, & André Maeder, Geneva Observatory

Very massive primordial stars ($140 M_{\odot} < M < 260 M_{\odot}$) are supposed to end their lives as Pair-Instability Supernovae (PISN). Such an event can be traced by a typical chemical signature in low-metallicity stars, but at the present time, this signature is lacking in the extremely metal-poor stars we are able to observe. Does it mean that those very massive objects were not formed, contrary to the primordial star formation scenarios? Could it be possible that they avoided this tragic fate? We explore the effects of rotation, anisotropic mass loss, and magnetic fields on the core size of very massive Population III models, in order to check if the central conditions are sufficiently modified so as to prevent the pair instability.

Long Gamma-Ray Bursts–Core-Collapse SN Connection

REVIEW

Andrew MacFadyen, New York University

I will review the GRB–SN connection in the context of the collapse and asymmetric explosion of massive rotating stars.

The Nature of Gamma-Ray Burst Progenitors: Observational Constraints

Kris Stanek, The Ohio State University

I will discuss the observational constraints we have on the GRB progenitors. I will concentrate on the properties of the hosts of nearby GRBs, contrasting them with what we know about hosts of various types of supernovae.

Stellar Evolution at Low Metallicity

REVIEW

Raphael Hirschi, Research Institute for the Environment, Physical Sciences & Applied Mathematics, Keele University; Cristina Chiappini, INAF Osservatorio Astronomico di Trieste; Georges Meynet, André Maeder, & Sylvia Ekström, Geneva Observatory

After recalling the difference between solar metallicity (Z) and low- Z stars, we will present the evolution and properties of low- Z stars. In particular, we will describe the possible effects and impact of rotation and mass loss on the evolution of low- Z stars and on stellar yields. We will compare the models with observations of extremely metal poor halo stars. I will end with a conclusion and an outlook.

Evolution of Progenitor Stars in Type Ib/c Supernovae and Long Gamma-Ray Bursts
Sung-Chul Yoon, University of California, Santa Cruz

There is growing evidence for the connection between SNe Ibc and long GRBs, suggesting that long GRBs are associated with deaths of massive stars. Progenitor stars of long GRBs seem to follow very different evolutionary paths from those of SNe Ibc progenitors, given that production of a long GRB requires a very rapidly rotating massive core within the collapsar scenario. Here we present massive single and binary star models that include the effects of rotation and magnetic torques on the chemical mixing and transport of angular momentum, and the exchange of mass and angular momentum in close binaries via tidal interaction and mass transfer. We discuss with emphasis the role of magnetic fields for the pre-SN/GRB evolution and their implications for the observed diversity of SNe Ibc and long GRBs.

WEDNESDAY, 12 December 2007
SESSION III: Massive Star Populations in the Nearby Universe

Young Massive Clusters

REVIEW

Donald F. Figer, Rochester Institute of Technology

Over the past ten years, there has been a revolution in our understanding of massive young stellar clusters in the Galaxy. Initially, there were no known examples having masses $>10^4 M_{\odot}$, yet now we know that there are at least a half dozen such clusters in the Galaxy. In all but one case, the masses of these clusters have been determined through infrared observations. Presumably, we are just scratching the surface, and we might look forward to having statistically significant samples of coeval massive stars at all important stages of stellar evolution. I review the efforts that have led to this dramatic turn of events and the growing sample of young massive clusters in the Galaxy.

Massive Stars in the Galactic Center

Fabrice Martins, MPE, Garching/GRAAL, Montpellier; R. Genzel, MPE, Garching; D. J. Hillier, University of Pittsburgh, et al.

We present recent results of the analysis of massive stars in the center of our Galaxy. Near-IR spectra of the central cluster and Arches cluster members are obtained with SINFONI on the VLT. They are analysed with the atmosphere code CMFGEN. The stellar and wind properties, including CN abundances, are derived. In the central cluster, 18 Wolf-Rayet stars are analysed. We find that they follow a normal stellar evolution in spite of the extreme environment and the presence of the supermassive black hole SgrA*. A direct link between Ofpe/WN9, WN8, and WN/C stars is established. The population of massive stars also produces the amount of ionising radiation required to account for the nebular emission in the central HII region. In the Arches cluster, 28 O supergiants and WNh stars are studied. The brightest components are very massive ($M \sim 120 M_{\odot}$) WNh7 stars. From the detailed study of their chemical composition, we identify them as core H burning objects showing products of the CNO equilibrium at their surface. Their wind properties are also investigated, and the findings support radiative driving for this class of WN stars. Altogether, these results provide new constraints on stellar evolution in the upper H-R diagram.

Metallicity Studies of Massive Stars in the Infrared: Unveiling the Obscured Clusters of Our Galaxy

Paco Najarro, Department of Molecular and Infrared Astrophysics, IEM-CSIC, Madrid

We review direct and indirect methods to derive metallicity through infrared spectroscopy of massive stars. The choice of different spectral types to obtain abundances allows us to trace metallicity for a wide range of ages of the cluster hosting the massive stars. These methods have a great potential to allow us to understand the evolution of a large amount of heavily obscured galactic clusters that are currently being discovered through infrared surveys.

Massive Stars in Nuclei and Arms of Spirals

REVIEW

Fabio Bresolin, Institute for Astronomy, University of Hawai'i

HII regions in external spiral galaxies provide us with a wealth of information regarding the properties of the ionizing stellar populations and the metal content of spiral disks. I will review some examples of this “indirect” view of massive stars in spiral galaxies, with particular attention to metal-rich objects and the comparison between nebular and stellar chemical abundances.

UCHII Regions and Newly Born O-type Stars

Peter Conti, JILA, University of Colorado; Jeonghee Rho, IPAC, Caltech; Paul Crowther & James Furness, University of Sheffield

All O stars go through a birth phase in which they are enclosed in a cocoon of dust and gas. This natal material can readily be found with radio observations as an ultra-compact ionized hydrogen (UCHII) region. We have obtained imaging of forty Galactic UCHII regions using the Spitzer IRAC and MIPS instruments. We show that in most cases multiple stars are found associated with the O star; thus these massive objects form in small clusters of sizes under 1 pc. In addition, in most cases, multiple starbirth activity is found nearby, within 5 pc; thus the O stars do not appear in isolation. The dust cocoons surrounding the exciting stars are typically a parsec in size, consistent with predictions of UCHII region models.

The Effects of N-body Stellar Dynamics on the Early Evolution of the Massive Star Population of Dense Star Clusters

Dany Vanbeveren, Brussel-Leuven; Houria Belkus, Brussel; Joris Van Bever, Institute for Computational Astrophysics, Saint Mary's University, Halifax

The early evolution of massive dense stellar systems (massive starbursts) is governed by massive single star and binary evolution in general and by dynamical N-body encounters of massive stars (single-single, single-binary, and binary-binary) in particular. Core collapse of dense massive star clusters is unavoidable, and this leads to the formation of very massive objects, with a mass up to $1000 M_{\odot}$ and even larger. When these objects become stars, stellar wind mass loss during core hydrogen burning and during core helium burning determines their evolution and final fate, and decides upon whether they form black holes (with normal mass or with intermediate mass) or explode as a pair instability supernova.

We first discuss evolutionary processes of massive stars and binaries which are important in order to understand the overall evolution of dense stellar systems, with special emphasis on the formation and evolution of very massive stars and of objects which are the product of physical collisions due to N-body stellar dynamics. A convenient evolutionary recipe for the very massive stars is presented that can readily be implemented in an N-body code.

Secondly, by linking a dynamical N-body code with an updated massive and very massive star evolution handler, we discuss (a) the effects of stellar dynamics on the early evolution of the massive star population in dense stellar systems (the OB star, the WR star, the O-type runaways with a space velocity >30 km/s and the massive binary population); (b) the effect of stellar dynamics combined with a realistic stellar wind mass loss formalism on the formation and evolution of very massive stars with an initial mass between $120 M_{\odot}$ and $1000 M_{\odot}$, on the occurrence of pair instability supernova, on the formation of intermediate mass black holes (with a mass $>100 M_{\odot}$) and on the model to explain ultraluminous X-ray sources; and (c) the effect of stellar dynamics on the spectral synthesis of starbursts.

Massive Stars in Dwarf and Irregular Galaxies

REVIEW

Eva K. Grebel, University of Heidelberg

I will discuss our knowledge of massive stars in resolved dwarf and irregular galaxies and the impact of these stars on the evolution of their host galaxies.

Westerlund 1 as a Template for Massive Star Evolution

Ignacio Negueruela, Universidad de Alicante; J. Simon Clark, Open University; P. A. Crowther, University of Sheffield, et al.

With a dynamical mass $>60,000 M_{\odot}$ and a lower limit $>50,000 M_{\odot}$ from star counts, Westerlund 1 is the most massive young open cluster known in the Galaxy and thus the perfect laboratory to study massive star evolution. We have developed a comprehensive spectral classification scheme for supergiants based on features in the 6000–9000 Å which allow us to identify >50 luminous supergiants in Westerlund 1. We will discuss their evolutionary connections, between themselves, to the large population of Wolf-Rayet stars and the huge population of O-type main-sequence stars. We also discuss the strong evidence for a very high similar-mass binary fraction among massive stars and present estimates of the mass and size of the cluster based on its massive star content.

One Hundred 30 Dor's: Is the Milky Way Different or Are We Somehow Missing Them?

Margaret Hanson & Bogdan Popescu, University of Cincinnati

There are a few ways to estimate the number of massive open clusters expected in the disk of the Milky Way, such as the total star formation rate of the Galaxy, or the open cluster mass function extrapolated to include the entire Galaxy. Surprisingly, they give similar predictions: the Milky Way should contain about 100 clusters as massive as 30 Doradus in the Large Magellanic Cloud, and even several clusters with 10 times that mass. Why don't we see them? This talk will first look closely at these predictions and compare them to what we have found so far in our Galaxy. I will then present sophisticated Monte Carlo imaging simulations our group is doing to estimate the selection biases faced by current near-infrared searches for these massive clusters.

THURSDAY, December 13, 2007**Session III: Massive Star Populations in the Nearby Universe (continued)****Extragalactic Stellar Astronomy with the Brightest Stars in the Universe** REVIEW

Rolf-Peter Kudritzki, Institute for Astronomy, University of Hawai'i

A supergiants are objects in transition from the blue to the red (and vice versa) in the uppermost H-R diagram. They are the intrinsically brightest “normal” stars at visual light with absolute visual magnitudes up to -9 , and thus, ideal to study young stellar populations in galaxies beyond the Local Group to determine chemical composition and evolution, interstellar extinction, reddening laws, and distances. The talk will summarize our knowledge of these objects based on high spectral resolution studies in the Milky Way and Local Group. It will then present the most recent results on the quantitative spectral analysis of such objects in galaxies beyond the Local Group based on medium- and low-resolution spectra obtained with the ESO VLT and Keck. We will describe the analysis method, discuss the determination of metallicity and metallicity gradients, and we will introduce a new method to measure accurate extragalactic distances based on the stellar gravities and effective temperatures obtained. Finally, we will discuss the perspectives of future work using the giant ground-based telescopes of the next generation such as the TMT, the GMT, and the E-ELT.

VLT Surveys of Wolf-Rayet Populations in Spiral Galaxies M83 and NGC 1313

Lucy J. Hadfield, Rochester Institute of Technology; Paul A. Crowther, University of Sheffield

We present results from a series of VLT/FORS narrow-band imaging and spectroscopic surveys of Wolf-Rayet (WR) stars in nearby ($D < 5$ Mpc) galaxies and compare observed populations in high- and low-metallicity environments. The metal-rich galaxy M83 is seen to host an exceptional WR content, with over 1000 WR stars being detected. $N(\text{WC})/N(\text{WN}) \sim 1.2$ and late-type WC subtypes dominate the WC population. At low metallicity, a modest WR population of ~ 100 stars has been identified within NGC 1313, with $N(\text{WC})/N(\text{WN}) \sim 0.5$. In contrast to M83, the WC population of NGC 1313 comprises solely early subtypes plus a WO star (the first WO star to be identified beyond the Local Group). Differences between observed WC subtype distributions are most naturally explained by metallicity-dependent WR winds, such that we suggest that the dominant WC subtype may serve as a metallicity diagnostic for WR galaxies.

THURSDAY, December 13, 2007**SESSION IV: Hydrodynamics and Feedback from Massive Stars in Galaxy Evolution****Bubbles and Superbubbles: Theory and Observations**

REVIEW

You-Hua Chu, Astronomy Department, University of Illinois

Massive stars inject kinetic energies into their ambient medium via fast stellar winds and supernova explosions. These dynamic interactions produce “bubbles” around isolated massive stars or “superbubbles” around groups of massive stars. Bubbles and superbubbles have multi-layered structures, including hot interiors that emit in X-rays, warm ionized shells that emit at optical wavelengths, and an interface layer where collisionally ionized gas can be observed in UV. The advent of Chandra, XMM-Newton, HST STIS, and FUSE has made it possible to make detailed observations of bubbles and superbubbles. I will compare multi-wavelength observations of bubbles and superbubbles with theoretical models and point out possible causes for the discrepancies between theories and observations.

The Evolution of the Circumstellar and Interstellar Medium around Massive Stars

S. Jane Arthur, Centro de Radioastronomía y Astrofísica, UNAM, Morelia

Throughout their lives, massive stars modify their environment through their ionizing photons and strong stellar winds. Here, I present coupled radiation-hydrodynamic calculations of the evolution of the bubbles and nebulae surrounding massive stars. The evolution is followed from the main sequence through the Wolf-Rayet stage, and shows that structures are formed in the ISM out to some tens of parsecs radius. Closer to the star, instabilities lead to the breakup of swept-up wind shells. The photoevaporated flows from the resulting clumps interact with the stellar wind from the central star, which leads to the production of soft X-rays. I examine the consequences for the different observable structures at all time and size scales and evaluate the impact that the massive star has on its environment.

Spitzer and ISO Observations for Studying the Mass-Loss Histories and Wind-Wind Interactions of Massive Stars with Circumstellar Nebulae

Pat Morris, Caltech, et al.

Mid-infrared observations of hot massive stars and their environments provide a detailed picture of mass-loss histories, dust formation, and dynamical interactions with the local stellar medium that can be unique to the thermal regime. Star formation triggered in interaction zones can be seen where cool material is optically obscured by dust. We have acquired infrared spectroscopy and spectacular imaging of some of the best known examples of hot stars with circumstellar nebulae, using instruments on the Spitzer Space Telescope, supplemented with archival Infrared Space Observatory data, and find new evidence for star formation triggered at more local scales than seen before, and interactions of winds created over several epochs with unprecedented detail with implications on the formation of these nebulae. We will summarize the observations in these recently completed guaranteed time and guest observing programs, focusing on NGC 2359 and M1-67 (WR), AG Car (LBV), G79.29+00.46, and HDE 316285 (B1e/LBVc). These data offer new perspectives on the interactions of the winds with the ISM over the course of evolution of the stellar cores.

Massive Star Feedback: Starbursts and Superwinds

REVIEW

Mike Dopita, RSAA, The Australian National University

Throughout cosmic time, the feedback of massive star winds and supernova explosions has been instrumental in determining the phase structure of the interstellar medium, controlling important aspects of both the formation and evolution of galaxies, producing galactic winds and enriching the intergalactic medium with heavy elements. In this talk, I will review progress in our understanding of how these feedback processes have operated from the time of the first stars up to the present day.

Massive Stars, Super Star Clusters, and Feedback in Starbursts

Jay Gallagher, University of Wisconsin; L. J. Smith, ESA/STScI; M. S. Westmoquette, University College London

The majority of stars now in existence likely formed in conditions more similar to those in starbursts than to the situation in the present-day solar neighborhood. Unique features in the spatial and temporal patterns of massive star formation in starbursts thus must be taken into account in understanding how feedback shaped galaxies. This talk considers how the concentration of massive stars into compact star clusters with sizes of ~ 10 pc, which in turn often are found in multi-100-pc-scale “starburst clumps,” affect the host galaxy. M82 provides a particularly accessible example of the starburst clump evolutionary mode. HST and ground-based observations show that the resulting high power densities can energize large-scale galactic winds and also support long-term photoionization over kpc scales. Working from the case of M82 we consider how changes in patterns of star formation can influence galaxy evolution through the redistribution of baryons and newly synthesized metals.

Gemini/IFU Observations of Galactic Outflows in Starburst Galaxies

Linda Smith, Space Telescope Science Institute

We present Gemini/IFU observations sampling the roots of the galactic wind outflows in NGC 1569 and M82. The good spatial and spectral resolutions of these observations allow us to probe the interactions of cluster winds with their environments on small scales. We find a ubiquitous underlying broad $H\alpha$ component which we associate with the impact of cluster winds on cold gas clumps. We discuss the diagnostic potential of this feature in terms of mass-loading and mass entrainment of cold gas into galactic winds. Our data also offer new insights into the formation of galactic winds; the lack of bulk motions close to the clusters indicates that the starburst regions are quasi-static, and that the sonic point is located at distances of 100–200 pc from the disk.

Radiative Feedback in Starburst Galaxies

Sally Oey, University of Michigan; G. R. Meurer, Johns Hopkins University; S. Yelda, UCLA, et al.

New results from the SINGG $H\alpha$ galaxy survey show that starburst galaxies have a lower fraction of diffuse, warm ionized medium than normal star-forming galaxies. Possible causes for this effect include a decrease in the ionizing contribution from field OB stars, absorption of radiation by dust, and the escape of ionizing radiation from these galaxies. We discuss these possibilities, of which the last is especially consequential and intriguing.

Role of Massive Stars in the Chemical Evolution of Galaxies

REVIEW

Francesca Matteucci, Astronomy Department, University of Trieste

Massive stars are the most important producers of metals in the Universe: in particular they are responsible for producing the alpha elements and part of Fe. Moreover, massive stars explode as Type II and Ib/c SNe, injecting large quantities of energy into the interstellar medium of galaxies. In this review, I will discuss the effects of massive stars on the chemical evolution of galaxies of different morphological types (ellipticals, spirals, and irregulars), as well as their role in triggering galactic winds. The link between Type Ib/c SNe and gamma-ray bursts will be also discussed.

Detailed Nucleosynthesis Yields from the Explosions of Massive Stars

Carla Fröhlich, Enrico Fermi Institute, University of Chicago; F.-K. Thielemann & T. Fischer, University of Basel, et al.

Despite the complexity and uncertainties of core collapse supernova simulations there is a need to provide correct nucleosynthesis abundances for the progressing field of galactic evolution and observations of low-metallicity stars. Especially the innermost ejecta is directly affected by the explosion mechanism, i.e. most strongly the yields of Fe-group nuclei for which an induced piston or thermal bomb treatment will not provide the correct yields because the effect of neutrino interactions is not included.

We present detailed isotopic composition for a wide range of progenitor stars ($13\text{--}35 M_{\odot}$), based on models for the supernova ejecta with accurate Boltzmann neutrino transport and detailed neutrino-matter interaction in the nuclear network. The yields will be discussed focussing on the initial mass (and composition) and the explosion energy. In addition, the impact of these yields on Galactic chemical evolution will be addressed.

FRIDAY, 14 December 2007**SESSION V: Massive Stars as Probes of the Early Universe****Massive Stars at High Redshifts**

REVIEW

Max Pettini, Institute of Astronomy, University of Cambridge

In the five years since IAU Symposium 212 in Lanzarote, our knowledge of the stellar populations and physical conditions in high-redshift galaxies has progressed enormously. In this brief review, I shall focus on different measures of the metallicity, stellar ages, and the high-mass end of the initial mass function in star-forming galaxies at $z = 2-3$. I will also discuss recent determinations of the abundances of elements in the CNO group in metal-poor environments, with the aim of uncovering clues to the nucleosynthesis by the earliest massive stars. I will conclude by highlighting some important open questions.

Massive Star Populations in $z = 3$ to 7 Starbursts

Daniel Schaerer, Geneva Observatory

We present a new analysis of high redshift galaxies selected from blank field and gravitational lensing surveys observed with ground-based telescopes, HST, and Spitzer in the optical to IR. New submillimeter observations of some objects are also included. We use evolutionary synthesis model fitting and apply a new 3-D Lyman- α radiation transfer code to interpret broadband photometric observations as well as the Lyman- α line emission strength and profile where possible. From our detailed modeling, we obtain new information on their massive star content, star formation histories, ages of the stellar populations, stellar masses, and on the importance of dust in these objects. Finally, the intrinsic production of ionising photons from these galaxies is constrained. The importance and interest of multi-wavelength observations including deep near-IR imaging, HERSCHEL, APEX, and ALMA of gravitational lensing clusters to study the populations of massive stars in the early Universe will also be illustrated.

Massive Star Formation in Galaxies beyond $z = 5$

REVIEW

Yoshiaki Taniguchi, Physics Department, Ehime University

We present a summary of recent observations of galaxies beyond $z = 5$ and then discuss massive star formation in the early Universe.

Core-Collapse Supernovae as Dust Producers in the Early Universe

Rubina Kotak, Queen's University Belfast, et al.

Recent years have witnessed a flurry of studies that have emphasised the important role that dust plays in our understanding of the near and distant Universe. Dust formation in the interstellar medium (ISM) has been shown to be extremely inefficient. The preferred sites for dust formation are the atmospheres of evolved, low-mass ($M < 8 M_{\odot}$) stars from where it is transported into the ISM via stellar winds. However, this mechanism fails to explain the presence of dust at high redshifts as the evolutionary time-scales of these low-mass stars (up to 1 Gyr) begin to become comparable to the age of the Universe. Furthermore, the IR luminosities of $z > 6$ quasars imply enormous dust masses ($10^8 M_{\odot}$). The short time-scales required for dust enrichment make core-collapse supernovae rather natural candidates for dust producers in the early Universe. Yet, direct evidence that grains condense in such supernovae is extremely sparse. As warm grains emit most strongly in the mid-IR, it is the ideal wavelength range for following dust condensation in real time. Since the launch of the Spitzer Space Telescope, we have begun a vigorous programme of mid-IR supernova studies. Here, I will discuss recent exciting results, and attempt to put the role of core-collapse supernovae as dust producers into perspective.

Gamma-Ray Bursts as Probes of High- z Galaxies

REVIEW

Johan Fynbo, Jens Hjorth, & Paul Vreeswijk, Dark Cosmology Centre, University of Copenhagen, et al.

Gamma-ray bursts (GRBs) constitute a powerful probe of high- z galaxies. GRBs allow us to localize high- z galaxies that, due to their faintness, are extremely difficult if not impossible to localize with other methods. Moreover, spectroscopy and imaging of the afterglows of GRBs provide a wealth of information on the state of chemical enrichment, dust content, and internal kinematics of high- z galaxies. The currently operating Swift satellite has given the field a tremendous boost due to its frequent, very rapid, and precise localisations of, on average, much more distant GRBs than previous GRB missions. In this talk I give a short review of the most important conclusions we have made from the last 3 years of Swift operation concerning GRBs and their host galaxies.

Probing the ISM and Stellar Environments of GRB Host Galaxies

Miroslava Dessauges-Zavadsky, Geneva Observatory; Jason X. Prochaska, UCO/Lick Observatory; Hsiao-Wen Chen, University of Chicago, et al.

We study the chemical abundances of the interstellar medium (ISM) surrounding high-redshift gamma-ray bursts (GRBs) through the analysis of the damped Lyman- α systems (DLAs) identified in afterglow spectra. These GRB-DLAs are characterized by very large HI column densities and metallicities spanning 1/100 to nearly solar, with median $[M/H] > -1$ dex. The majority of GRB-DLAs have $[M/H]$ values exceeding the cosmic mean metallicity of atomic gas at $z > 2$. We also observe (i) large $[Zn/Fe]$ values ($>+0.6$ dex) and sub-solar $[Ti/Fe]$ ratios which imply substantial differential depletion, (ii) large $[\alpha/Fe]$ ratios suggesting nucleosynthetic enrichment by massive stars, and (iii) low C^0/C^+ ratios ($<10^{-4}$). Quantitatively, the observed depletion levels and C^0/C^+ ratios of the gas are not characteristic of cold, dense HI clouds in the Galactic ISM. This is in line with the non-detection of molecular H_2 lines in the GRB-DLAs. Given these results and the not especially anomalous abundance patterns, we argue that the GRB-DLA represents the ISM near the GRB but not gas directly local to the GRB (e.g., its molecular cloud or circumstellar material). A recent closer inspection of the afterglow spectra shows the almost ubiquitous presence of NV, whose presence and characteristics can only be explained by the GRB event itself. We additionally look for signatures of GRB stellar progenitors in the afterglow spectra. Following the observational evidence we found in three nearby GRB host galaxies and the theoretical predictions for Wolf-Rayet (WR) stars as long GRB progenitors, we re-investigate the possible presence of WR winds.

The Connection between Gamma-Ray Bursts and Extremely Metal-Poor Stars as Nucleosynthetic Probes of the Early Universe

Ken'ichi Nomoto, Department of Astronomy, University of Tokyo

The connection between the long GRBs and Type Ic Supernovae (SNe) has revealed the following interesting diversity: (1) GRB-SNe, which explode with extremely high energies, thus being called Hypernovae (HNe). (2) Non-GRB HNe: Some HNe are not associated with GRBs. (3) XRF-SN: SN 2006aj associated with X-Ray Flash 060218 may be powered by a magnetar rather than a black hole. (4) Non-SN GRB, i.e., dark HNe. I will show that nucleosynthetic properties found in the above diversity are connected to the variation of the abundance patterns of extremely metal-poor stars, such as the excess of C, Co, and Zn relative to Fe. Such a connection can be modeled in a unified manner, and used to probe the nature of massive stars in the early universe. (Nomoto et al. astro-ph/0702472, 0605725; Tominaga et al. ApJ 657, L77 & ApJ 660, 516).

The First Stars

REVIEW

Volker Bromm, Department of Astronomy, University of Texas

The emergence of the first stars and galaxies at redshifts 30–15 signaled the transition from the simple initial state of the Universe to one of ever increasing complexity. I review recent progress in understanding their formation with numerical simulations, starting from cosmological initial conditions and modelling the detailed physics involved. Specifically, I will discuss the case for a top-heavy IMF of Population III stars. I will conclude by discussing promising observational diagnostics that will allow us to probe the properties of the first stars, such as their contribution to reionization and the chemical abundance pattern observed in extremely low-metallicity stars.

Imprint of the First Stars Era in the Cosmic Infrared Background Fluctuations

Alexander (Sasha) Kashlinsky, Goddard Space Flight Center

The cosmic infrared background (CIB) contains emissions from the entire history of the Universe, including the epochs of the first stars. We (Kashlinsky, Arendt, Mather, & Moseley 2005, 2007a,b) have recently detected excess CIB fluctuations over that from ordinary galaxies using deep Spitzer/IRAC data and suggested that it originates from the first stars era. I will discuss the measurements and their interpretation. The data require a population with at most a fairly low level of shot noise, but a significant large-scale CIB component arising from clustering. This suggests a population of sources in the first Gyr of the Universe with individual fluxes <10 nJy ($3.6 \mu\text{m}$) that were much more luminous than the present-day stellar population. I will also discuss the prospects for their individual detection with the future space instruments.

Imaging and Spectroscopy with the James Webb Space Telescope

George Sonneborn, Goddard Space Flight Center

The James Webb Space Telescope (JWST) is a large, cryogenic infrared-optimized space telescope scheduled for launch in 2013. JWST will find the first stars and galaxies that formed in the early Universe, connecting the Big Bang to our own Milky Way galaxy. JWST will peer through dusty clouds to see stars forming planetary systems, connecting the Milky Way to our own Solar System. JWST's instruments are designed to work primarily in the infrared range of 1–28 microns, with some capability in the visible range. JWST will have a large mirror, 6.5 meters in diameter, and will be diffraction-limited at 2 microns (0.1 arcsec resolution). JWST will be placed in an L2 orbit about 1.5 million km from the Earth. The instruments will provide imaging, coronagraphy, and multi-object and integral-field spectroscopy across the full 1–28 micron wavelength range. The breakthrough capabilities of JWST will enable new studies of massive star formation and evolution in the Milky Way, nearby galaxies, and the early Universe.

Studying Massive Stars with Instrumentation at the E-ELT

REVIEW

Sandro D'Odorico, ESO, Garching

At the 8–10 m class telescopes like the Keck, ESO VLT, Gemini, and Subaru, the second generation of instruments is already under construction. In parallel, studies have also been started on instruments for the new class of 20–50 m telescopes. Massive stars in the Galaxy and in external galaxies figure prominently in the science cases for these instruments. The extremely large telescopes in particular will offer unique performances in terms of collecting power and angular resolution. An overview of the prospects for the European ELT is presented in the framework of other facilities expected to be operative in the second decade of this century.

Conference Summary

Claus Leitherer, Space Telescope Science Institute

I will summarize the main ideas and new trends in massive star research presented at this conference.