The Evolution of Massive Stars: The Be Star and Microquasar Phenomena

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Abstract

Massive O- and B-type stars evolve significantly faster than stars with cooler spectral types, so their populations include stars at many different evolutionary stages. They provide fascinating laboratories for the study of stellar evolution. In this dissertation, I investigate an unevolved massive star system as well as two particular categories of evolved stars, Be stars and microquasars.

The massive triple system HD 16429 A is largely unevolved, but I present it here as an example of the type of system that will eventually experience a disrupting supernova. I discuss the Doppler tomography technique that I used to isolate the two brightest components and my analysis of each star. The stationary component, HD 16429 Aa, is an O9.5 II star. The Ab1 component is a hotter yet less luminous O8 III-IV star, while the unseen Ab2 star is estimated to be a B0 star.

Many massive binary systems, including Be binaries, contain the final product of massive stellar evolution: a neutron star or black hole companion. Mass transfer from the less evolved star onto the compact companion generates X-ray emission, and some of these massive X-ray binaries (MXRBs) also have relativistic radio jets that

closely resemble small versions of extragalactic quasars. In this dissertation I perform a spectroscopic study of the microquasar LS 5039. Based on its large eccentricity and runaway velocity, LS 5039 appears to be a recent survivor of the supernova that formed the microquasar.

Be stars are a class of B stars with circumstellar disks that cause Balmer and other line emission. The source of their disks is not well understood, but it is likely that a combination of rapid rotation and other processes contribute to their formation. There are three possible reasons for their rapid rotation: they may have been born as rapid rotators, spun up by binary mass transfer, or spun up during the MS evolution of B stars. To investigate these three formation scenarios, I am performing a photometric survey of open clusters. In this work I present the results from the first 20 clusters.

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My sisters, Suzanne and Lauren, have also been very supportive during my graduate school career. Although the three of us have become more physically separated during the past few years, moving across the country to various schools and jobs, we are becoming closer to each other than ever. It is comforting to know that I will always be able to rely on them in any situation.

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Contents

List of Tables

List of Figures

Abbreviations

3α	triple alpha
A&A	Astronomy & Astrophysics
A&AS	Astronomy & Astrophysics Supplement Series
AAS	American Astronomical Society
AJ	Astronomical Journal
ARA&A	Annual Reviews of Astronomy & Astrophysics
ApL	Astrophysical Letters
ApJ	Astrophysical Journal
ApJS	Astrophysical Journal Supplement Series
CCD	charge coupled device
CEP	common envelope phase
CF	Coudé Feed
CNO	carbon-nitrogen-oxygen
CS	Cassegrain Spectrograph
CTIO	Cerro Tololo Inter-American Observatory
FUV	far ultraviolet
FWHM	full-width at half-maximum
HR	Hertzsprung-Russell
HST	Hubble Space Telescope
HWHM	half-width at half-maximum
IUE	International Ultraviolet Explorer
KPNO	Kitt Peak National Observatory
LCS	Large Cassegrain Spectrograph
LTE	local thermodynamic equilibruium
McD	McDonald Observatory
MNRAS	Monthly Notices of the Royal Astronomical Society
MS	main-sequence

MXRB	massive X-ray binary
NAC	narrow absorption components
PASP	Publications of the Astronomical Society of the Pacific
pp	proton-proton
PSF	point-spread function
RLOF	Roche lobe overflow
SN	supernova
S/N	signal-to-noise ratio
STIS	Space Telescope Imaging Spectrograph
TAMS	terminal-age main-sequence
UV	ultraviolet
ZAMS	zero-age main-sequence

Chapter 1

Introduction

Massive O- and B-type stars evolve significantly faster than stars with cooler spectral types, so their populations include stars at many different evolutionary stages. They provide fascinating laboratories for the study of stellar evolution. In this dissertation, I investigate two particular categories of evolved stars, Be stars and microquasars.

Be stars are a class of B stars with circumstellar disks that produce Balmer and other line emission. The source of their disks is not well understood, but it is likely that rapid rotation, combined with nonradial pulsations or magnetic fields, contributes to their formation (Porter & Rivinius 2003). This phenomenon is observed both in pre-main-sequence and evolved B stars, although here I concentrate on main-sequence (MS) and post-MS Be stars. These classical Be stars may develop among B stars that are born as rapid rotators, or the phenomenon may occur later during their lifetimes. Recent evolutionary models of rapidly rotating massive stars have suggested that the Be phenomenon may be caused by an evolutionary spin-up towards the end of the MS lifetime (Meynet & Maeder 2000). Alternatively, binary mass transfer may be responsible for the increase in rotational velocity that induces the Be star disks, although not all Be stars are observed in binary systems.

Many massive binary systems, including Be binaries, contain the final product of massive stellar evolution: a neutron star or black hole companion. Mass transfer from the less evolved star onto the compact companion generates X-ray emission, and some of these massive X-ray binaries (MXRBs) also have relativistic radio jets that closely resemble small versions of extragalactic quasars. Not only are microquasars a good testbed for accretion disk and jet models, they provide fascinating examples of stellar evolution. For example, LS 5039 appears to be a recently formed microquasar, and many of its pre-supernova characteristics can be derived from spectroscopic studies of the system.

Before I examine these particular examples of stellar evolution, I present a broader discussion of stellar evolution in general. The processes involved during the MS evolution of O- and B-type stars are discussed in §1.1, and their post-MS evolution is described in §1.2. Finally, close binary systems such as HD 16429 Ab and the progenitor to LS 5039 will undergo unique evolutionary processes due to binary interactions, and such close binary evolution is discussed in §1.3. Finally, in §1.4 I present an outline of my investigations for each object.

1.1 Massive Stars on the Main-Sequence

The most important factor that influences a star's life on the MS is its mass. More massive stars have higher core and surface temperatures, greater initial luminosities, and more energy generation in their cores to provide radiation pressure and support them against their own gravity. To accomodate their excesses in luminosity and energy generation, the lifetimes of massive stars are shortened significantly compared to solar and lower mass stars. In this section I review the structure of massive stars on the MS, the methods of energy generation and energy transport in their interiors, and the effect of increasing the mean molecular weight as H is converted to He. I also mention several other factors that influence MS evolution, namely metallicity, convective core overshooting, and rotational velocity. Unless otherwise specified, this discussion of MS (and post MS evolution in §1.3) is from Kippenhahn & Weigert (1990).

When stars begin their core H burning at the zero-age main-sequence (ZAMS), they are generally assumed to be chemically homogeneous and in mechanical and thermal equilibrium. The internal structure of a spherically symmetric star can be described by the differential equations of stellar structure. Mass conservation defines the relationship between the mass distribution inside the star, m, the density, ρ, and the radius, r, such that

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho}. \tag{1.1}$$

Stars are assumed to be in hydrostatic equilibrium in which the difference in pressure, P, across any element within the star is equal to the force of gravity; therefore

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4}, \tag{1.2}$$

where G is the gravitational constant. The luminosity distribution, $l(m)$, within the star depends on the nuclear energy generation rate, $\epsilon_{\rm n}$, energy loss from neutrinos, ϵ_ν, and internal energy released from the gas:

$$\frac{\partial l}{\partial m} = \epsilon_{\rm n} - \epsilon_\nu - c_P \frac{\partial T}{\partial t} + \frac{\delta}{\rho}\frac{\partial P}{\partial t}. \tag{1.3}$$

Here, c_P is the specific heat at constant pressure, and the temperature T and pressure P may change over time, t. The coefficient δ is defined as

$$\delta \equiv -\left(\frac{\partial \ln \rho}{\partial \ln T}\right)_P. \tag{1.4}$$

Finally, the temperature distribution within the star is given by the expression

$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P}\nabla, \tag{1.5}$$

where ∇ is defined as

$$\nabla \equiv \frac{d \ln T}{d \ln P}. \tag{1.6}$$