Paper for ASTR 8100 Class

King of the Stellar Heap - Observational Evidence for the Most Massive Stars

Ben Team[1]

Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303

ABSTRACT

This is a brief analysis of the observational evidence for the upper mass limit for stellar objects. Current observational information suggests that this limit is approximately $150M_\odot$ (Kroupa & Weidner 2005). Several of the most massive stars are described in terms of observational characteristics and the difficulties encountered in trying to determine the upper mass limit for stars.

Subject headings: Stellar UML, Pistol Star

1. Introduction

When children are introduced to new ideas, often they ask many simplistic, yet critical questions trying to identify the boundaries of the new idea based on their existing knowledge base. Questions like "What is the largest?", "What is the smallest?", or "What is the fastest?" are often asked. Answers to these simple questions often have implications far beyond just the simple answers.

This paper will explore the answer to one such simple question. What is the upper mass limit (UML) of a star? There are two methods of answering this question. The first is to define the limit based on theoretical modeling of the physics of stellar formation using detailed knowledge of these processes. Alternatively, the limit may be identified by observations of stellar populations, which is the methodology utilized herein.

Stellar population inventories will likely never be able to completely identify the precise UML of all stars, but with enough samples, the limit can be statistically identified. To

[1]Graduate Student, Astronomy Program, Georgia State University, Atlanta, GA 30303

this end, a few published stellar surveys will be examined to provide observational evidence for this limit. Several of the most massive stars identified to date will also be identified as candidates for the most massive star.

2. Background

In order to put the search for the UML in perspective, a short historical discussion of both the theoretical limits and the observational limits follows. This paper will arbitrarily define 1970 as the point on the time line of history that separates references into contemporary and historical categories.

2.1. Historical UML Theories

In 1936, Jaakko Tuominen (Tuominen 1936), in reference to papers on the upper mass limits of stars published by Vogt(1929) and by Thuring(1936) states "...that the existence of such a limit is very unlikely, ...". Later in the twentieth century, following the work by Ledoux(1941) and later by Schwarzschild and Harm(1959), the astronomical community recognized the theoretical stellar upper mass limit as 65 $M_{\odot}$. This was based primarily on the limits imposed by the Eddington luminosity relationship of L_{Edd} / $L_{\odot} \approx 3.5 \times 10^4$ $m/\mathrm{M}_{\odot}$ for stars with a balance of radiation pressure and gravity.

2.2. Historical Observations

As part of his work in 1965, Benjamin Peery identifies the primary component in VV Cephi (HD 208816) as having a Msin(i) = 84.4$\mathrm{M}_{\odot}$ and the secondary component as having a Msin(i) = 41.3$\mathrm{M}_{\odot}$ (Peery 1966). Although this observation was of a binary system, the combined mass of the system was almost twice the theoretical limit of the time. Alan Batten cataloged numerous spectroscopic binary systems in 1968 and found that the only exception to the UML of 65$M_{\odot}$ was the primary component of the VV Cephi system, which he dismissed as being not well established (Batten 1968).

2.3. Modern Survey Requirements

The brute force method of identifying the the stellar UML would be to measure the masses of every star in the visible universe. This would absolutely guarantee an answer, subject only to a few constraints, but would be unrealizable in any amount of realistic time due to the vast number of stars in the visible universe. Thus a more reasoned approach is required, one which will reduce the scope of the stellar population to be examined. Reducing the sample size reduces the both the telescope time requirements and the post-observation data analysis requirements simultaneously. Knowledge of several fundamental properties of massive stars can lead to judicious choices of regions to observe that might provide the highest probability of observing the most massive star and identifying the most massive star.

The most massive stars often exhibit characteristics like strong stellar winds or mass ejections that result in rapid mass loss (Figer et al. 1998). These stars are also generally extremely luminous. These characteristics generally reduce the stellar lifetime compared to more normal stars like the sun. In order to locate stars like this, one must identify aging stellar nurseries or young star clusters. Observing the stars in star-burst clusters is one way to optimize the observational requirements.

One promising theory of stellar formation in clusters is that consecutively more massive stars form until the UML is reached (Kroupa & Weidner 2005). Therefore the available mass of the proto-stellar material and the masses of existing stars should be evaluated carefully to determine whether a particular cluster is a good candidate for observation.

Luminous blue variables (LBVs) are stars that are generally thought to be the evolutionary link between massive main sequence O stars and evolved Wolf-Rayet stars. These are ideal candidates for observational surveys searching for the most massive stars.

3. Massey's 1995 Survey of the Northern Milky Way

Massey et al. (1995) observed more than 10,000 stars in clusters and OB association in his investigation of the initial mass function (IMF) for this region. A comparison was made between the Northern Milky Way (NMW) and the Magelanic Clouds (MCs). The regions Cygnus OB2 and Trumpler 14/16 in particular are identified as hosting massive stars.

The UBV photometry for this study used the KPNO 0.9 m telescope coupled to a Tecktronix 2048 x 2048 CCD over 5 nights in October 1990. The CCD images were reduced using IRAF routines. The spectroscopy was performed on the KPNO 4 m telescope using a multiobject Hydra fiber positioner coupled to a bench mounted spectrograph during September

1991 and during October 1992 . HR diagrams were produced from the reduced data.

From isochrones on the HR diagrams derived from this survey the Cyg OB2 region has 4 stars with masses between $85M_{\odot}$ and $120M_{\odot}$ while the Tr 14/16 region shows 3 stars with masses greater than $85M_{\odot}$ and two of those have masses greater than $120M_{\odot}$. It is not clear how massive the most massive star is because isochrones are not shown for masses greater than $120M_{\odot}$. Massey concludes that the masses of the highest mass stars among the observed NMW and MC associations is approximately the same.

4. Herrero's Analysis of Cygnus OB2

Herrero et al. (Herrero et al. 1999) performed spectral analysis on 11 OB stars in Cygnus OB2. Seven of these stars studied are classified as giants or supergiants.

The spectroscopic observations were performed using the 2.5 m Isaac Newton Telescope at the Roque de los Muchachos Observatory on La Palma. Data reduction was done using IRAF routines.

Three different masses for each star are tabulated, the spectroscopic mass, the present evolutionary mass, and the initial evolutionary mass. Cyg OB2 22 is identified as an O4 III(f) star having an initial evolutionary mass of $131M_{\odot}$ and a current evolutionary mass of $118.7M_{\odot}$, while Cyg OB2 516 is identified as an O5.5 V((f)) star having an initial evolutionary mass of $123M_{\odot}$ and a current evolutionary mass of $100.1M_{\odot}$. Herrero also indicates that he saw no evidence of binarity that might skew the results.

5. Massey's 2004 Sample of the R136 Cluster

In this survey Massey et al. (2004) used HST and CTIO telescopes to perform spectroscopy on twenty O-type stars in the R136 cluster.

The observation were done in three spectral bands: 1) in 120 - 190 nm, 2) in the blue-optical region, and 3) in the Hα region. CALSTIS and IRAF routines were used to reduce the data.

The results of the analysis indicated that no stars in the sample were more massive than $100M_{\odot}$.

6. Figer's 1998 Pistol Star Observations

Figer et al. (Figer et al. 1998) used a combination of the 3 m Shane telescope, the Keck I telescope, and the UKIRT telescope to take images and spectra of the Pistol Star on various nights from July 1994 through July of 1997 in JHK'nbL bands as well as the 1.88, 2.18, and 4.05 μm bands. IRAF and FIGARO routines were used to reduce the data. ndfigure

The Pistol Star spectrum is similar to that of LBV and B[e] stars. The spectral characteristics of HD 72754 are are very similar to the Pistol Star in the K-band, but therefore, primarily lacks the He I absorption lines and the unique Pistol Star emission line near 2.149μm. Other stars with similar spectral characteristics in general include S Dor and η Car. Changes in the Brackett-γ level over the various observing runs indicate potential changes in the ionization structure of the stellar winds. The Pistol Star is suggested to be classified as a LBV currently in a quiescent phase similar to P Cygni. Also the Pistol Nebula surrounding the star is suggested to be $\approx 11 M_{\odot}$ of photoionized ejecta.

Analysis of the line-of-sight velocities and ages of the Pistol Star and stars belonging to the Quintuplet cluster indicate they are all part of the same physical cluster near the galactic center. The calculated luminosity has an upper bound of $10^{7.2}L_{\odot}$ at a en effective temperature of $\approx 10^{4.15}$ K. Because the most luminous components of R136 and η Car have both been shown to be binary systems, the K-band images were examined for indications of binarity. Speckle data show that the Pistol Star does not show signs of a binary companion down to the limit of a separation of 110 AU.

See figure 2 for a photograph of the Pistol Star and the surrounding nebula.

7. Figer's 2005 Examination of The Arches Cluster

Although there is no accepted value for the stellar UML (Figer 2005), Figer proposes that the limit should be $\approx 150 M_{\odot}$ based on the analysis the stellar mass distribution in the Arches cluster. In clusters the following relationship generally holds for masses $\approx 1 M_{\odot}$

$\mathrm{d}(\log N)/d(\log m) = \Gamma = -1.35$

where N is the number of stars and m is the stellar m. For clusters with a total stellar mass $\geq 10^4 M_{\odot}$, there should be at least one star with a mass $\geq 150 M_{\odot}$. Based on the observed distribution of stellar masses and either an approximation based on the observed Γ or on the Salpeter value (Salpeter 1955), there is a deficit of stars with such high masses in the cluster.

The age of the cluster has a major impact on the probability of observing a star at or near the UML. LBVs and other OB stars live short lives after after arriving at the ZAMS point on the HR diagram. For example, in a cluster like the Arches, if the cluster is older than ≈ 3 Myr then the most massive members would no longer be visible.

See figure 3 for a photograph of the Arches cluster.

See figure 4 for a chart indicating the frequency of stellar masses vs the mass distributions in the Arches cluster.

8. Conclusion

Carsten Weidner and Pavel Kroupa (Weidner & Kroupa 2006) in their paper relating the UML to cluster formation have included this table which summarizes many of the most recent observations of massive stars. This data supports Donald Figer's UML value of $150M_{\odot}$

Designation	M_{ecl} ($M_{\odot}$)	m_{maxobs} ($M_{\odot}$)	Age (Myr)	Source
Taurus–Auriga	25 ± 15	2.2 ± 0.2	1–2	(1)
Ser SVS2	30 ± 15	2.2 ± 0.2	2	(2)
NGC 1333	80 ± 30	5 ± 1.0	1–3	(3)
ρ Oph	100 ± 50	8 ± 1.0	0.1–1	(4)
IC 348	109 ± 20	6 ± 1.0	1.3	(5)
NGC 2024	225 ± 30	20 ± 4	0.5	(6)
σ Ori	225 ± 30	20 ± 4	2.5	(6)
Mon R2	259 ± 60	10 ± 1	0–3	(7)
NGC 2264	355 ± 50	25 ± 5	3.1	(8)
NGC 6530	815 ± 115	20 ± 4	2.3	(9)
Ber 86	1500 ± 500	40 ± 8	2–3	(10)
M42	2200 ± 300	45 ± 5	<1	(11)
NGC 2244	6240 ± 124	70 ± 14	1.9	(12)
NGC 6611	$2 \times 10^4 \pm 10\,000$	85 ± 15	1.3 ± 0.3	(13)
Tr 14/16	$4.3 \times 10^4 -2.3 \times 10^4/+2 \times 10^4$	120 ± 15	<3	(14)
Arches	$5 \times 10^4 -3.5 \times 10^4/+2 \times 10^4$	135 ± 15	2.5	(15)
R136	$1 \times 10^5 -5 \times 10^4/+1.5 \times 10^5$	145 ± 10	1–2	(16)
Simulation	580	27	0.456	(17)

(1): Briceño et al. (2002); (2): Kaas et al. (2004); (3): Aspin (2003), Getman et al. (2002); (4): Wilking, Lada & Young (1989); Larson (2003); (5) Preibisch & Zinnecker (2001), Lada & Lada (2003); (6) Sherry, Walter & Wolk (2004); (7): Carpenter et al. (1997); (8): Sung, Bessell & Chun (2004); (9): Prisinzano et al. (2005), Damiani et al. (2004); (10): Massey, Johnson & DeGioia-Eastwood (1995); Vallenari et al. (1999); (11): Hillenbrand & Hartmann (1998), Hillenbrand et al. (1998); (11): Massey et al. (1995), Park & Sung (2002); (13): Bonatto, Santos & Bica (2005); (14): Massey & Johnson (1993), Massey et al. (1995); (15): Figer et al. (2002); (16): Massey & Hunter (1998), Selman et al. (1999); and (17): Bonnell et al. (2003)

Fig. 1.— Observed stellar masses and ages

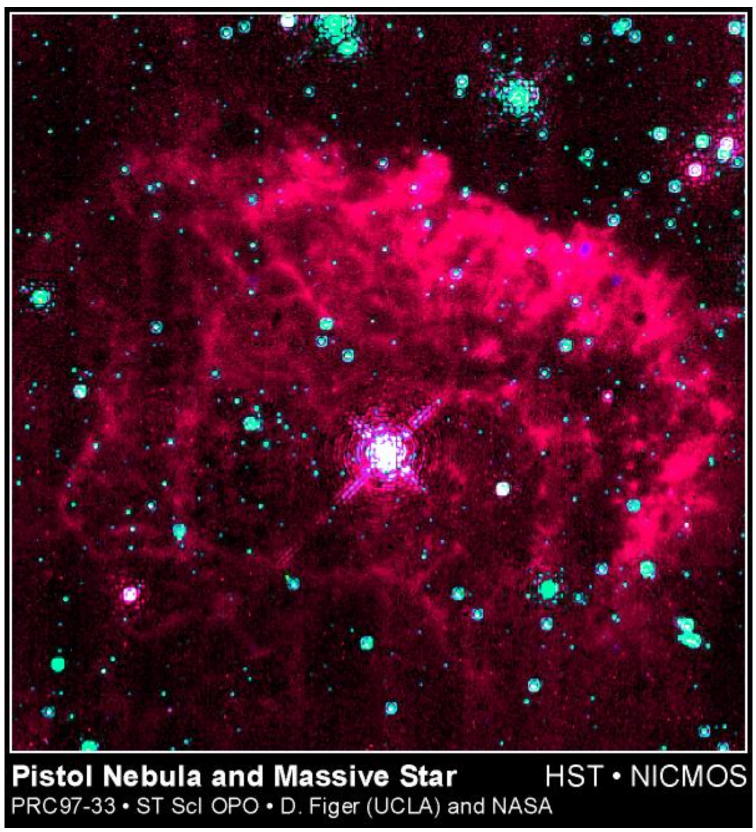

Fig. 2.— The Pistol Star and Surrounding Nebula

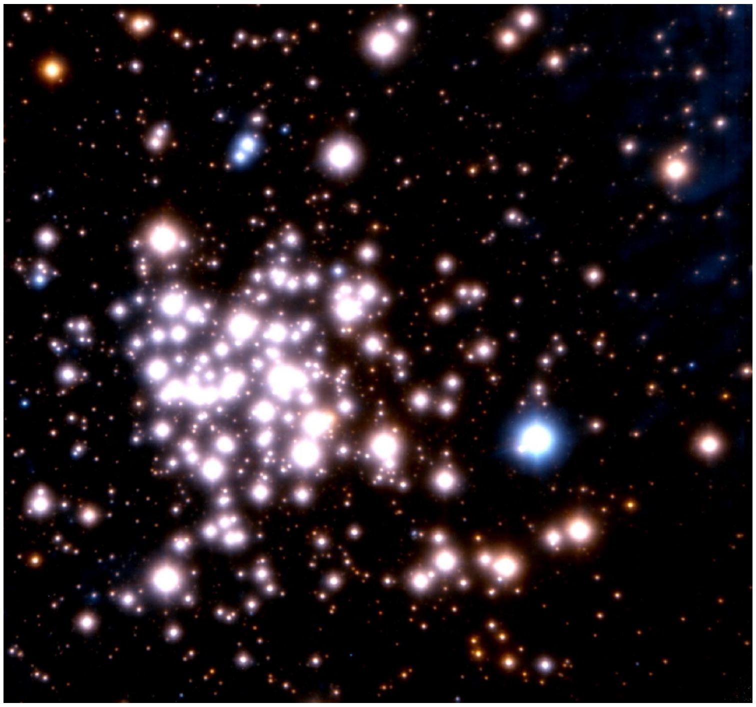

Fig. 3.— Photograph of The Arches Cluster. False color near IR image, J, H, K' bands, North is up, East is left, FOV 38.4 x 38.4", (Figer et al. 1998)

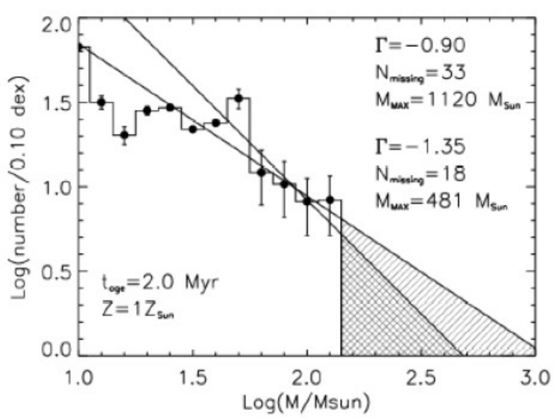

Fig. 4.— Frequency vs. mass distribution for the Arches Cluster. This shows a clear deficit of stars in the grey area at the right of the chart. (Figer 2005)

REFERENCES

Batten, A. H. 1968, AJ, 73, 551

Elson, R. A. W., Schade, D. J., Thomson, R. C., & Mackay, C. D. 1992, MNRAS, 258, 103

Figer, D. F. 2005, Nature, 434, 192

Figer, D. F., Najarro, F., Morris, M., McLean, I. S., Geballe, T. R., Ghez, A. M., & Langer, N. 1998, ApJ, 506, 384

Herrero, A., Corral, L. J., Villamariz, M. R., & Martín, E. L. 1999, A&A, 348, 542

Heydari-Malayeri, M., & Beuzit, J.-L. 1994, A&A, 287, L17

Hillier, D. J., Davidson, K., Ishibashi, K., & Gull, T. 2001, ApJ, 553, 837

Humphreys, R. M., & Davidson, K. 1994, PASP, 106, 1025

Humphreys, R. M. 1978, ApJS, 38, 309

Humphreys, R. M., & Davidson, K. 1979, ApJ, 232, 409

Iping, R. C., Sonneborn, G., Gull, T. R., Massa, D. L., & Hillier, D. J. 2005, ApJ, 633, L37

Kroupa, P., & Weidner, C. 2005, IAU Symposium, 227, 423

Larson, R. B., & Starrfield, S. 1971, A&A, 13, 190

Ledoux, P. 1941, ApJ, 94, 537

Massey, P., Bresolin, F., Kudritzki, R. P., Puls, J., & Pauldrach, A. W. A. 2004, ApJ, 608, 1001

Massey, P., Johnson, K. E., & Degioia-Eastwood, K. 1995, ApJ, 454, 151

Massey, P., Lang, C. C., Degioia-Eastwood, K., & Garmany, C. D. 1995, ApJ, 438, 188

Massey, P. 2002, ApJS, 141, 81

Massey, P. 2003, ARA&A, 41, 15

Massey, P. 1999, Bulletin of the American Astronomical Society, 31, 1462

Massey, P. 1999, IAU Symp. 190: New Views of the Magellanic Clouds, 190, 173

Najarro, F., & Figer, D. F. 1998, Ap&SS, 263, 251

Oey, M. S., & Clarke, C. J. 2005, ApJ, 620, L43

Peery, B. F. 1966, ApJ, 144, 672

Salpeter, E. E. 1955, ApJ, 121, 161

Schwarzschild, M., Harm, R. 1959, ApJ, 129, 637

Shylaja, B. S. 1997, Bulletin of the Astronomical Society of India, 25, 421

Thüring, B. 1936, Astronomische Nachrichten, 258, 97

Tuominen, J. 1936, Zeitschrift fur Astrophysik, 12, 72

Vogt, H. 1929, Veroeffentlichungen der Universitaets-Sternwarte zu Jena, 2, 1

Weidner, C., & Kroupa, P. 2006, MNRAS, 365, 1333