On The Empirical Formulation of Stellar Lifetime Based on Stellar Mass

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Abstract

An empirical determination of Stellar Lifetime Based on Stellar Mass was undertaken using published studies and raw, archival data. Based on ***The Standard Solar Model***, a hydrogen burning, stellar lifetime dependence on stellar mass was derived from the data. Lifetime, in this context, is strictly defined as the time a star is productively transforming its compliment of hydrogen into helium on the Main Sequence. As would be the case for any such study, the more high-quality data available, the more accurate a result is attainable. As such, extensive searches were conducted on MAST, in searches of the Astronomical Journal, the Astrophysical Journal and the Astrophysical Journal Supplemental letters.

Introduction

With the advent of spaceborne observing platforms combined with cutting-edge technology becoming available, the acquisition and processing of data and images of heretofore unprecedented quality and scope is available, providing the astrophysical community with the ability to refine and enhance existing stellar evolutionary models. Using raw, archival data along with data obtained through the analysis of peer-reviewed journals, the following analysis will present an empirical formulation of Stellar Lifetime based on Stellar Mass.

This research sprang from a problem (10.21, p 347) in Carroll and Ostlie, ***An Introduction to Modern Astrophysics***, Second Edition and reflects a particular research interest of mine. The problem in question asked the student to comment on and determine the lifetime of 2 stars, one a small, red dwarf at the Hydrogen burning mass limit (0.072 $M_{\odot}$) with the log of it's luminosity being -4.300 and the other star at the high end of the stellar-mass scale. At 85 $M_{\odot}$, the log of this star's luminosity relative to the sun is 6.006, a value that indicates a luminosity in excess of one million times the sun's! A very useful tool in any discussion of stellar evolution and stellar lifetimes would be an empirical expression for stellar lifetime based on stellar mass. Indeed, some modern problems in Astrophysics concern themselves with stellar mass and it is my intention to first, empirically derive an expression of stellar lifetime (how long a particular star will remain on the Main Sequence) based on mass and two, in doing so, to perhaps shed some light on some of the larger questions confronting our notions of time, matter, energy and the long-term evolution of the universe on a grand scale.

Method

In undertaking a task such as this, it is essential to obtain as much empirical data as possible. To empirically determine the projected age of any system, two variables are essential: the mass and the luminosity. Binary stars whose orbital solutions are known are ideal in that we can empirically determine their masses using Keplerian/ Newtonian dynamics. With the highly successful ESA Hipparcos satellite, very accurate distance determinations have been made out to 500 Ly. I have used Hipparcos data when possible and where appropriate. Accurate distance measurement is essential in the determination of intrinsic luminosity. In addition to binary stars, exoplanet searches have turned up much useful mass and orbital statistics. I have attempted to avail myself of as much of both empirically determined binary orbital solutions and exoplanet searches in my study as possible.

Combined with an empirically determined mass, an empirically determined luminosity is also ideal and much effort was expended locating empirical data rather than derived quantities. Again, space borne platforms have been key in determining ***intrinsic*** luminosities and I have made an exhaustive search for them in both peer-refereed journals and raw data.

For my study, I produced a basic Excel template ordered by mass, adding columns as appropriate and required. As stated, the other, basic parameter is luminosity and this column immediately follows the stellar mass. As a consequence of this study, the classic Mass/ Luminosity relation was derived and is included. A separate, minor study of the Mass/ Luminosity relation for stars at the low end of the Main Sequence is included. Much of the data for the low-mass stars (< 0.4 $M_\odot$) included in this study is of exceedingly high value, being obtained by HST STIS, NICMOS and FGS3. Additionally, with many high value resources being brought to bear in the search for exoplanets, I've included some of those host stars and their corresponding data in this study. Among those high-profile searches and discoveries, is the recent detection of Fomalhaut b with HST NICMOS. The detection of Fomalhaut b represents the first direct image of a planet in orbit around another star. Using the high-value, high-quality orbital data in the published Fomalhaut b study, a very accurate determination of the total system mass was obtained using a Keplerian/ Newtonian solution. That solution was used to tightly constrain the mass of the host star, Fomalhaut. Many such specific studies were undertaken, especially for the lower-mass regime, with their respective solutions and results used as input to the main study.

The fundamental premise [of this study] is straight forward: any particular star's lifetime is determined simply by how much fuel is available for nuclear fusion reactions and what the rate of those reactions is. Said differently, at what rate (luminosity) is the star's compliment of hydrogen (mass) consumed? The total energy expended, therefore, is the product of the stars luminosity and the time over which that luminosity is achieved: $E = L\,t$. Energy is also given by $E = mc^2$. Equating the two, we write $L\,t = mc^2$. Solving for t, we write $t = \frac{mc^2}{L}$. It needs to be stated that, for the purposes of this study, a star's lifetime is considered to be the time between the star's ZAMS point to the cessation of hydrogen fusion reactions through the P-P Chain or the CNO Cycle. The study includes stars near the Hydrogen burning mass limit, 0.072 $M_\odot$, to stars at the upper end of the stellar-mass scale, 85 $M_\odot$, as well as several massive, evolved stars, including Eta Carinae. Because of their short, punctuated lifetimes, massive stars represent a small portion of the stellar population; as such, there seems to be a dearth of available raw data or peer-reviewed studies of them suitable for inclusion in this study; this is part of the reason why several massive, evolved stars were included [in the study].

The low end of the Main Sequence is represented by the 4 stars in the GJ2005 system. At 0.072 $M_\odot$, GJ2005D represents a star close to the Hydrogen burning mass limit; the upper end of the Main Sequence stellar-mass limit is represented by Theta^1 Orionis C at 45 $M_\odot$, HD 64568 at 57 $M_\odot$ and the 85 $M_\odot$ star that was part of the exercise in Carroll & Ostlie. While decidedly evolved and not a Main Sequence star, Eta Carinae, at 120 $M_\odot$, represents a star at the upper end of the Main Sequence where a system in hydrodynamic equilibrium can remain stable, is one where its data, when fitted with and alongside other Main Sequence data in the study, was consistent with that data and, when charted, is consistent with the overall slope and function of the various charts produced. Stars in this mass regime, where the extraordinarily high reaction rates necessary to support the huge masses produce a fierce stellar wind, approach the Eddington Limit, a boundary condition where the inwardly directed gravitational potential is equal to the outward radiation pressure.

As both ends of the Main Sequence represent tests for current stellar models, with the ***Standard Solar Model*** as a basis for these models, it is my intention to provide new insights into the validity and veracity of the models.

It is an oversimplification to state that 10% of a given star's mass will be used over its productive, Main Sequence lifetime. A more rigorous formulation would take into account the 0.71% energy efficiency of the P-P Chain or the CNO cycle, the primordial abundances: X_0= 0.73 Hydrogen, Y_0= 0.25 Helium, Z_0= 0.02 Metals, that only 25% of X_0 will be available for energy production (4 H → 1 He) and, of the total stellar mass for solar-mass-size stars, the inner 70% contained within 0.3 R is what will be used to achieve its Main Sequence luminosity. We adopt a more rigorous formulation than to simply state that the total energy expended over a particular star's lifetime is $E = 0.1mc^2$; that formulation is specified below under **Nuclear Burning**. In the principal columns, those stars that are currently on the Main Sequence, a color-coded font is provided. Non Main Sequence stars are indicated with the standard, black font.

There are 3 high-value, computed columns in the principal table:

1. **Hydrogen Burning Lifetime (M/L Computed)**
   This column represents the computed, hydrogen-burning lifetime of a given star and is based on the computed, hydrogen burning lifetime based on mass, luminosity and the principles outlined briefly above and, in more detail below, under the heading **Nuclear Burning**. The results computed in this column and its associated column, **Hydrogen Burning Lifetime (Generic-Fitted),** ***represent the core results and objects of this study***;
2. **Hydrogen Burning Lifetime (M/M(s)^2.5 Empirical**)
   This column represents the computed hydrogen burning lifetime based on the ***individually-computed Mass-Luminosity relation*** for each of the sampled stars. This column was included for comparison purposes only;
3. **Hydrogen Burning Lifetime (Generic-Fitted)**
   This column is based on the computed, hydrogen burning lifetime based on mass, luminosity and the principles outlined briefly above and, in more detail below, under the heading **Nuclear Burning.** The formulation for each cell in this column was populated using the empirically derived lifetime function, specified under **Results, #3** and, along with 1, above, ***represent the core results and objects of this study***. As was the case for all functions and analyses in this study, this empirically derived lifetime function was obtained using the statistical data analysis subset of Microsoft Excel®.

The Plank Function

We conduct a related study, included in a separate worksheet. Entitled "Plankfunction", a manual integration of the Plank Function is provided for various temperatures. The formal integration of the Plank function will provide the total bolometric luminosity for a given temperature. As such, our results are approximate, as we adopted a differential wavelength of 10 nanometers.

Nuclear Burning

In the computation of 1, above, 3 separate, mass-based formulations were used. The basic premise is, as stated above, that the star's productive time on the Main Sequence will be given by $t = \frac{mc^2}{L}$, that, for solar-mass-size stars 70% of the star's ***hydrogen*** abundance (X_0= 0.73 M) will be available for burning via the P-P Chain or the CNO Cycle, that only 25% of that mass will be will be converted into energy and that energy production has a 0.71% efficiency. Taking these conditions into account we build the following, fundamental relationship: $t = \dfrac{\frac{0.0071}{4}\left(\frac{m}{M_{\odot}}\right)M_{\odot}\,x\left(2.99x10^{8}\right)^{2}}{\left(\frac{l}{L_{\odot}}\right)L_{\odot}}$ seconds. Each cell in the column referenced in 1, above, is converted to years. So as to express it in terms approximately equal to one solar lifetime, that result, in turn, is expressed in units of 10^{10} years in a subsequent column.

1. For stars 0.45 $M_{\odot}$ and below, a fully-convective interior is posited. Due to the higher interior opacities [resulting from the lower temperatures, pressure and density requirements] of this sub-Solar-mass classification, the star is fully convective with its full compliment of hydrogen available for nuclear burning. This will significantly extend the star's lifespan. The formulation we adopt for these low-mass stars is T= 0.73 t, where t is specified above.
2. For stars between 0.4 $M_{\odot}$ and 2.0 $M_{\odot}$, due to the higher temperatures, pressures and densities, we adopt a radiative core out to 0.3 R. The ***Standard Solar Model*** indicates that 0.7 M is contained within 0.3 R, that 100% of the star's luminosity is achieved at 0.3 R and the star will remain on the Main Sequence, in hydrogen-burning hydrodynamic equilibrium, until 0.12 of its core hydrogen abundance remains. This limit effectively reduces the available mass by 12%. At this point, the star will evolve off the Main Sequence, ascend the RGB of the H-R Diagram and follow the mass-appropriate path. For the sun, this occurs at 11.7 gyr after its ZAMS point according to our calculations, a result that corresponds very well with figure 1, below. Adapting t, according to the above conditions, we write:
$T = ((0.7x0.73) - (0.511x0.12))t$
$T = (0.511 - (0.511x0.12))t$
$T = 0.44968t$

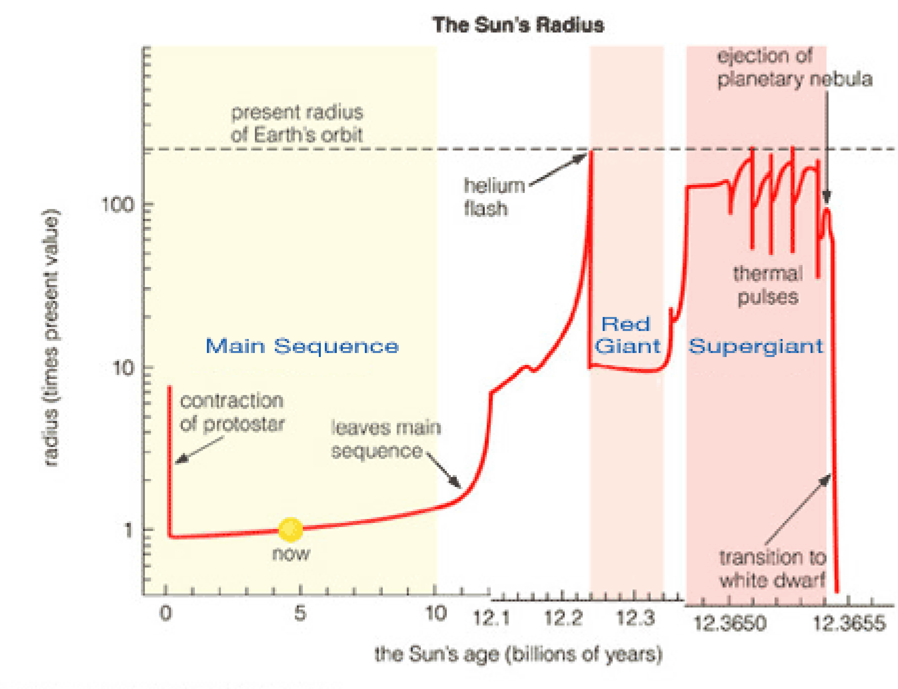

Figure 1 illustrating the evolution of a 1 $M_{\odot}$ star

3. For stars over 2.0 $M_{\odot}$, due to the higher reaction rates necessary to support the increased stellar mass, the higher temperatures, pressures and densities, a convective core is adopted out to 0.3R where the opacity is driven by the high density of free electrons. In as much as the internal evolution and structure of higher mass stars is mass-dependant, with the requirement of a mass-specific model, we adopt a standard formulation for stellar lifetime of T = (0.7x0.73)t or 0.511t for high mass stars.

Correlations

Good correlation between specific computed lifetimes and fitted, generic-mass solutions is observed for stars in all mass regimes. Several stars in the 12 – 20 $M_{\odot}$ range are worthy of note; specifically, the 15 $M_{\odot}$ star Mu Columbae, where high-quality data was available, a Main Sequence lifetime of 6.4 million years is computed; that, with a corresponding generic-mass solution of 13.9 myr, compares favorably with the 11.5 myr Main Sequence lifetime cited in various peer-refereed articles concerning stars in this mass regime as well as peer-refereed articles discussing progenitor candidates for Type II Supernovae. As well, the 18 $M_{\odot}$ star Pi Andromedae, with a computed Main Sequence lifetime of 11.96 million years and a fitted, generic-mass solution of 8.4 myr, also compares favorably with lifetimes in this mass regime.

Well correlated examples in the low-mass regime include:

1. GJ2005A, at 0.090 $M_{\odot}$, has a specific, computed lifetime of 3.1 tyr with a fitted, generic-mass solution of 5.4 tyr. Unlike GJ2005A, GJ2005D, with an effective temperature of 1698 K, has a computed lifetime of 27 tyr, falls well below the trendline in the M-L relation for low mass stars and, with its exceedingly low luminosity, represents an object ***at the mass limit*** for hydrogen burning;
2. The sun, with a 11.7 gyr computed lifetime and a generic-mass, fitted lifetime of 12.6 gyr, corresponds very well with the evolutionary track of a 1 $M_{\odot}$ star as illustrated in Figure 1.

A cursory examination of the luminosity for stars of equal mass but of differing projected lifetimes would indicate that, for stars where the fitted, generic-mass solution approaches the computed lifetime of the specific star, either the star's empirically observed data is of very high quality where the value either of the luminosity or the mass is very close to theory or, for a few of the stars sampled, the values were derived using Kurucz model atmospheres as a basis.

For those specific stars in the sampling where there is more than a 50% difference in the generic-mass solution and the ***specific solution for that star***, that star has either evolved off the Main Sequence, its luminosity is uncharacteristically high or low for the particular mass regime or the mass and/ or luminosity is a derived quantity.

Results

Using the data analysis subset of Microsoft Excel®, the following are the various derived quantities. Mass and luminosity, unless otherwise indicated, are in solar units.

1. Derived Mass-Luminosity relation (all sampled stars; Figure 2); this is the standard Mass-Luminosity relation, often described as L = $M^{3.5}$:
    a. $Log\ L = 3.4751 \log M + 0.06$
    b. $L = 1.148M^{3.4751}$
2. Derived Mass-Luminosity relation (low-mass stars <= 0.45 $M_{\odot}$; Figure 3):
    a. $Log\ L = 2.5212 \log M - 0.6451$
    b. $L = .2264M^{2.52}$
3. Derived Hydrogen burning stellar lifetime function, T, as a function of stellar mass (Figures 4 & 5); note: this function represents ***the core result and principal object*** of this study;
    a. $LogT_{(yrs)} = -2.5162 LogM + 10.1$
    b. $T_{(yrs)} = 1.259x10^{10} M^{-2.5162}$
4. Derived Hydrogen burning stellar lifetime function, T, computed using the individually computed Mass-Luminosity relation of each of the sampled stars (Figure 6). Included for reference only.
    a. $LogT_{(yrs)} = -2.4746 LogM + 9.9404$
    b. $T_{(yrs)} = 8.718x10^{9} M^{-2.4746}$

Illustrations

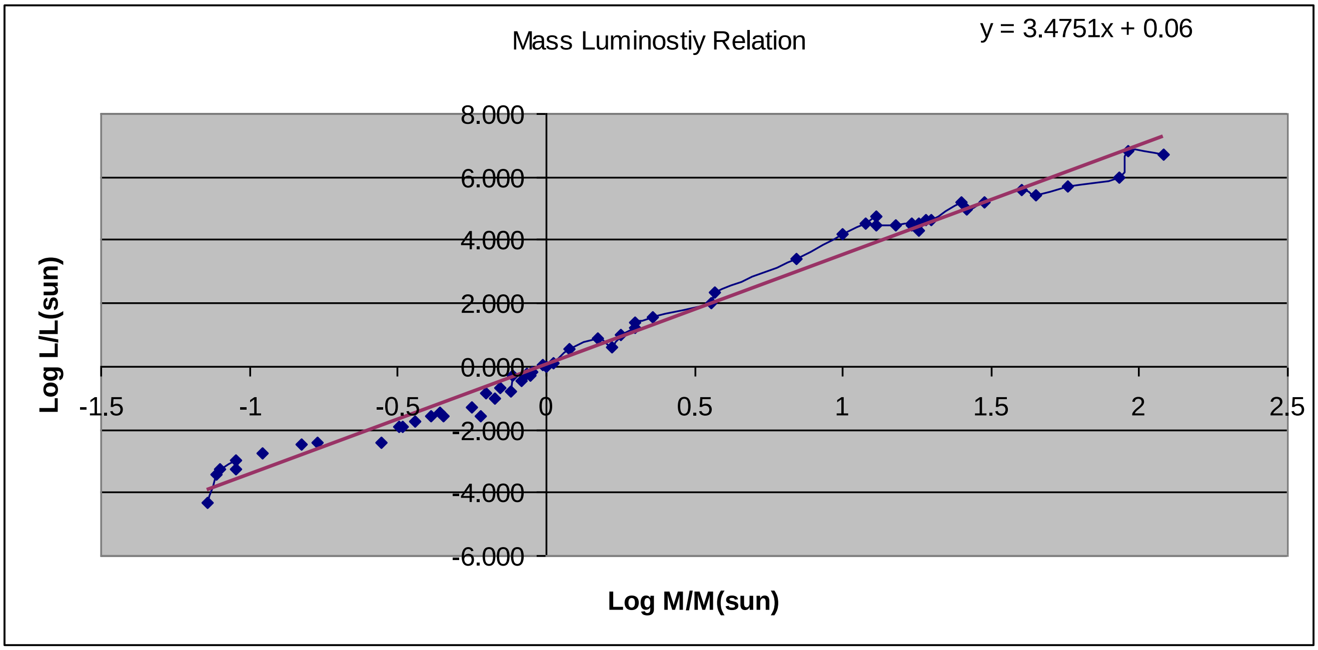

Figure 2 log-log plot illustrating this study's empirically derived Mass-Luminosity relation

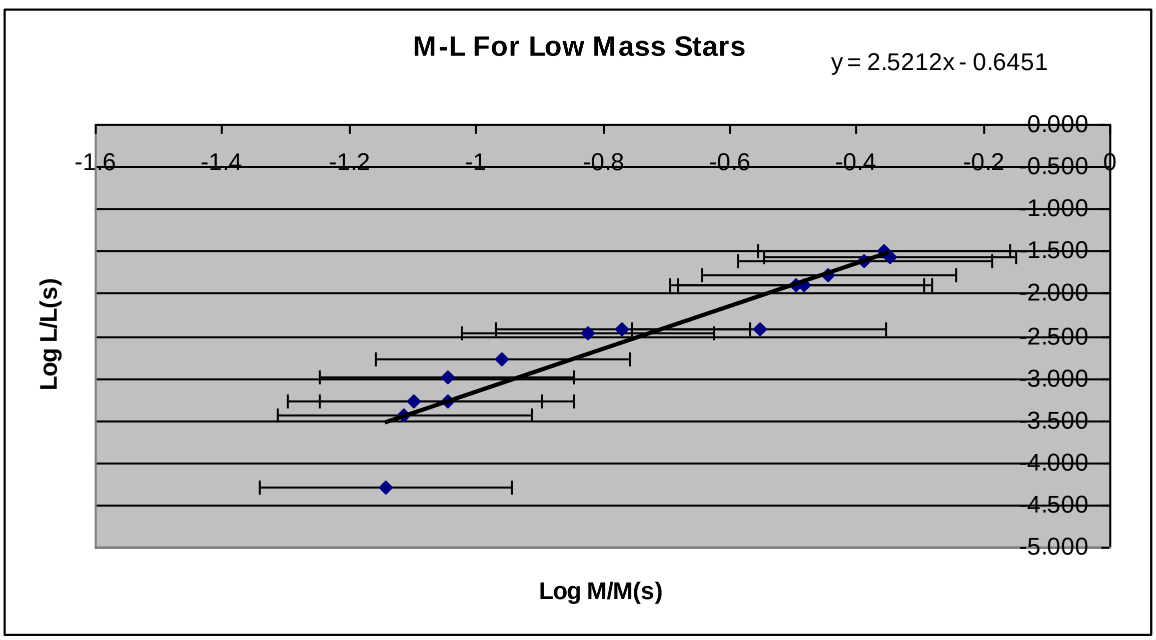

Figure 3 log-log plot illustrating this study's empirically derived Mass-Luminosity relation for low-mass stars <= 0.45 $M_{\odot}$

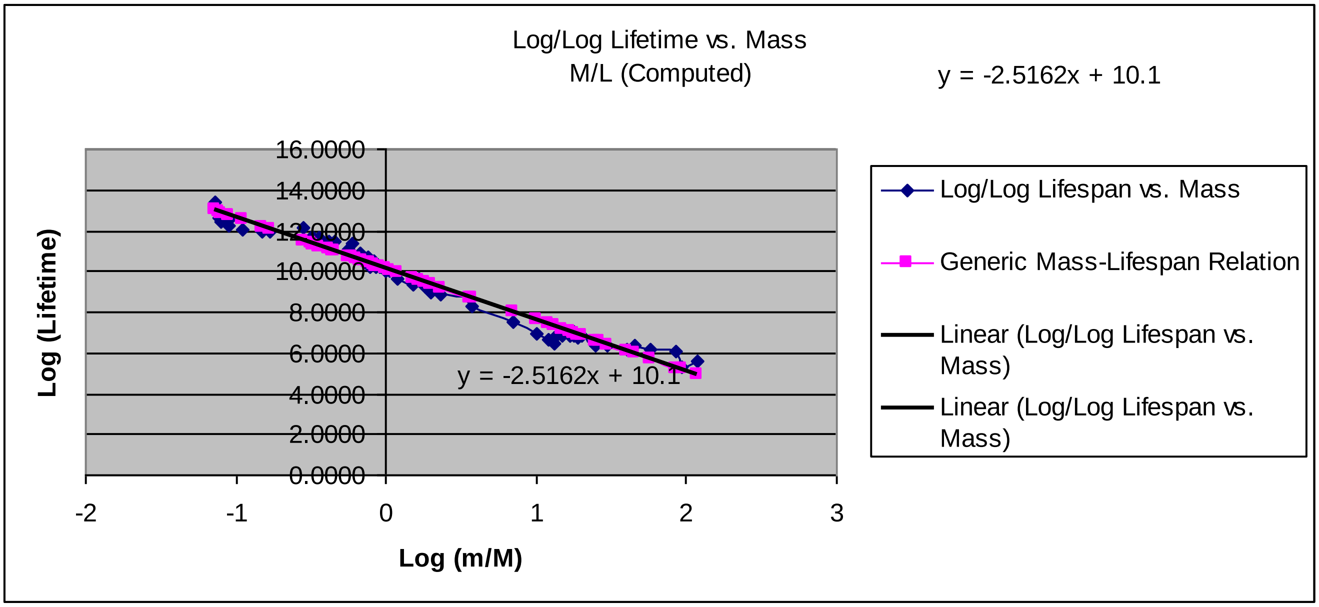

Figure 4 illustrating the log-log plot of the Stellar Lifetime function. This function represents ***the core result and principal object*** of this study

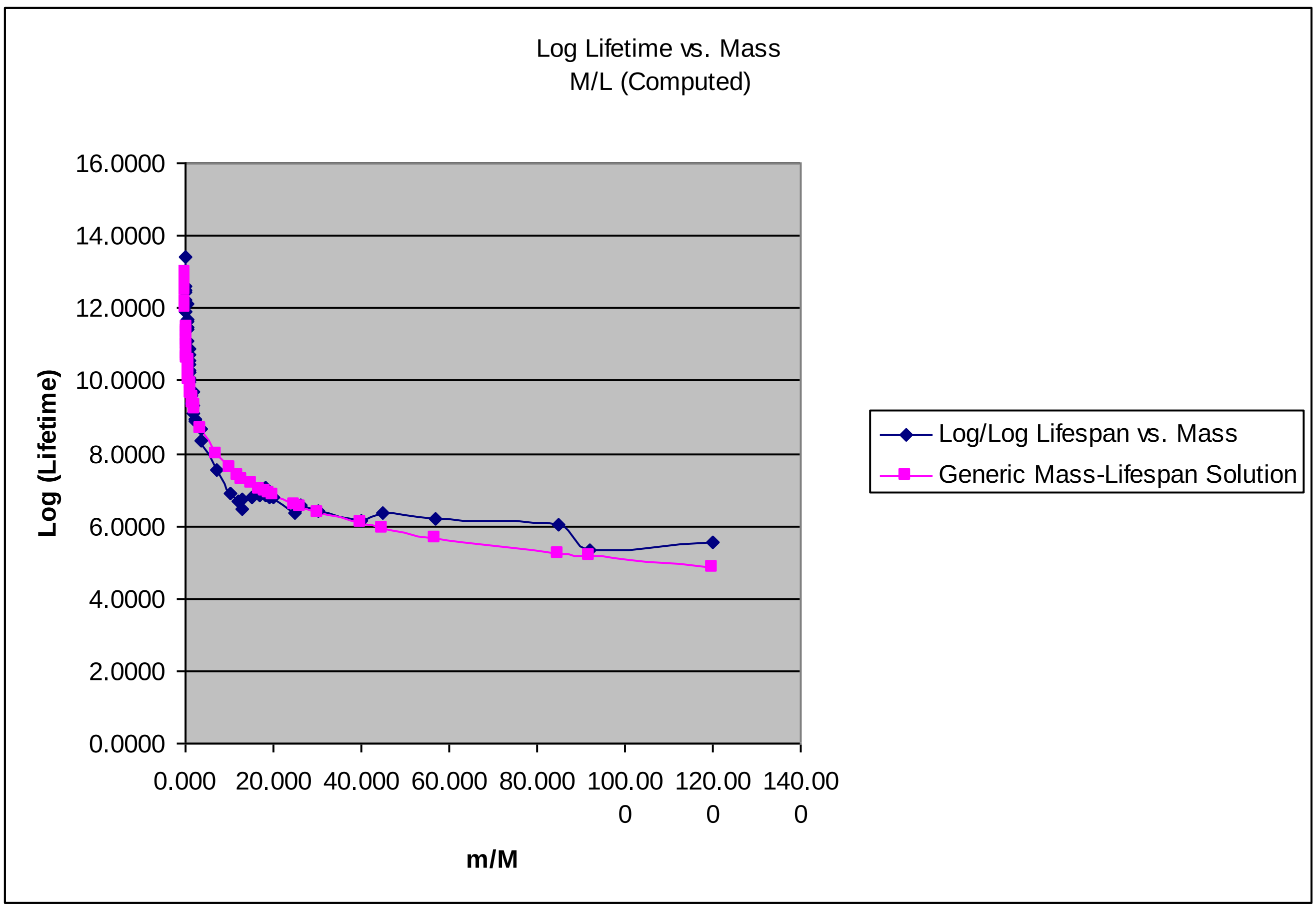

Figure 5 illustrating the log plot of Stellar Lifetime as a function of mass. The blue plot represents all of the individual sampled stars. The pink plot represents the derived Mass-Lifetime relation as a generic function of mass. As indicated in Table 1, there is a good correlation between the plotted data, represented in blue and the derived, generic function, represented in pink

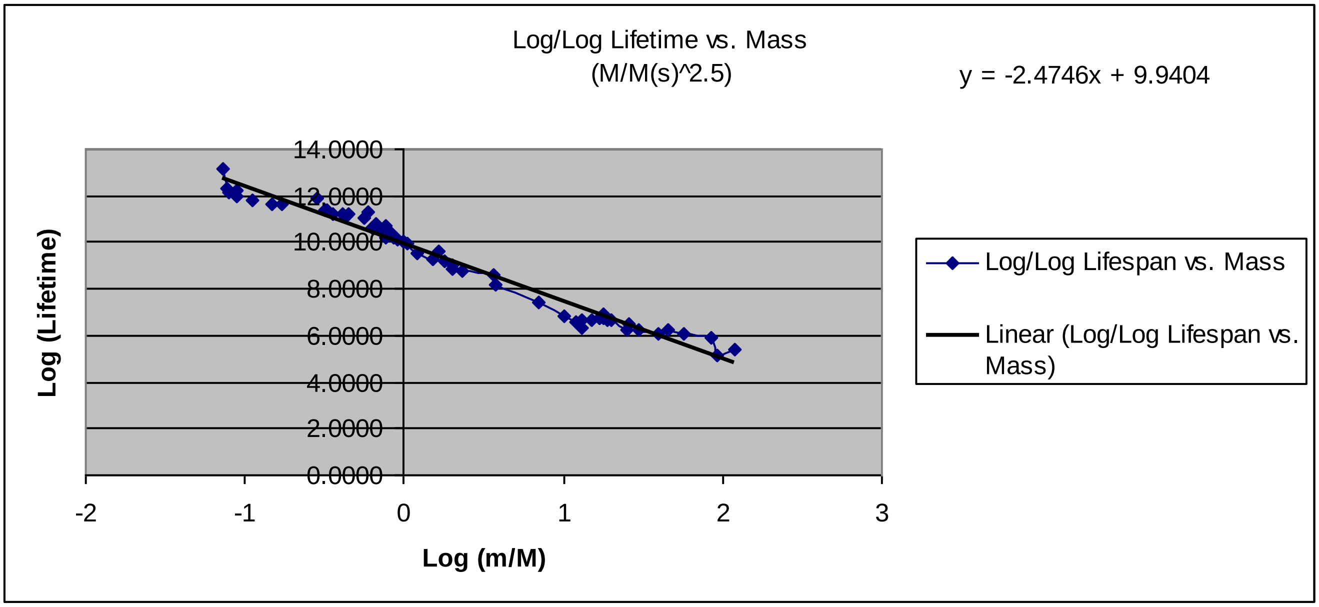

Figure 6 illustrating the log-log plot of the Stellar Lifetime function using the standard Mass-Luminosity relation. This chart plots the individually computed Mass-Luminosity relation of each of the sampled stars

Tables

Table 1 illustrating the core results and objects of this study. Color coded rows represent Main Sequence stars and data

Mass	**Luminosity (Sun = 1)**	**Hydrogen Burning Lifetime (M/L Computed)** 10^10 yrs	**Hydrogen Burning Lifetime (M/L Computed)** Years	**Hydrogen Burning Lifetime (M/M(s)^2.5** Years	**Hydrogen Burning Lifetime (Generic-Fitted)** Years	**Hydrogen Burning Lifetime (Log – Generic-Fitted)** Years	**Star**	**Spectral Type**
0.072	5.0119E-05	2726.236558	2.7262E+13	1.4366E+13	9.44452E+12	12.97517997	LHS1070 D / GJ 2005D	M9 V
0.077	3.6644E-04	398.769346	3.9877E+12	2.1013E+12	7.97649E+12	12.90181204	LHS1070 C / GJ 2005C	M9 V
0.080	5.2481E-04	289.281745	2.8928E+12	1.52437E+12	7.24511E+12	12.86004497	LHS1070 B / GJ 2005B	M8.5 V
0.090	1.0130E-03	168.602537	1.6860E+12	8.8845E+11	5.38685E+12	12.731335	Wolf 359 / GJ406	M6.5 Ve
0.090	5.5005E-04	310.508541	1.2279E+12	1.63622E+12	5.38685E+12	12.731335	LHS1070 A / GJ 2005A	M5.5 V
0.110	1.7000E-03	122.793338	1.2279E+12	6.47059E+11	3.25123E+12	12.51204773	Proxima Centauri	M5.5 Ve
0.150	3.4300E-03	82.990462	8.2990E+11	4.37318E+11	1.48977E+12	12.17311917	Barnards Star	M4 Ve
0.170	3.8000E-03	84.897786	8.4898E+11	4.47368E+11	1.08729E+12	12.03634442	Ross 154	M3.5 V
0.280	0.00383	138.736361	1.3874E+12	7.3107E+11	3.09785E+11	11.49106096	Kapteyn's Star (HD 33793)	M1 VI (sd)
0.320	0.0124	48.973296	4.8973E+11	2.5806E+11	2.21382E+11	11.34514162	Gliese 876	M3.5 V
0.330	0.0130	48.172771	4.8173E+11	2.5385E+11	2.04887E+11	11.31151522	Gliese 581	M3 V
0.380	0.0171	42.268286	4.2268E+11	1.7956E+11	1.64601E+11	11.21643165	Gliese 570 C	M3 V
0.410	0.0250	31.122530	3.1123E+11	1.6400E+11	1.18662E+11	11.07431326	Gliese 436	M2.5 V
0.440	0.0325	25.692145	2.5692E+11	1.3538E+11	9.93446E+10	10.99714438	Gliese 832	M1.5 V
0.450	0.0269	31.706678	3.1707E+11	1.6708E+11	9.38829E+10	10.97258667	Lalande 21185	M2 V
0.560	0.0530	12.359468	1.2359E+11	1.0573E+11	5.41513E+10	10.73360929	Gliese 570 B	M1 V
0.600	0.028	25.049841	2.5050E+11	2.1429E+11	4.55214E+10	10.65821582	Lacaille 8760 (GL 825)	M2 Ve
0.630	0.15	4.909769	4.9098E+10	4.2000E+10	4.02624E+10	10.60489931	61 Cygni B	K7 V
0.670	0.101	7.754703	7.7547E+10	6.6337E+10	3.44850E+10	10.53763058	Groombridge 1618; GJ380	K7 V
0.700	0.215	3.806022	3.8060E+10	3.2558E+10	3.08862E+10	10.48976431	61 Cygni A	K5 V
0.760	0.16000	5.552715	5.5527E+10	4.7500E+10	2.51129E+10	10.39989684	Gliese 570 A	K4 V
0.770	0.52	1.731008	1.7310E+10	1.4808E+10	2.43003E+10	10.38561204	Tau Ceti	G8 V
0.830	0.33	2.903286	2.9033E+10	2.4836E+10	2.01194E+10	10.3036157	Epsilon Eridani	K2 V
0.860	0.55	1.827879	1.8279E+10	1.5636E+10	1.83999E+10	10.264815	HD 61005	G8 V
0.890	0.51	2.040007	2.0400E+10	1.7451E+10	1.68789E+10	10.22734487	70 Ophiuchi A	K0 V
0.900	0.65	1.618605	1.6186E+10	1.3846E+10	1.64110E+10	10.215135	14 Herculis	K0 V
0.980	1.18	0.970858	9.7086E+09	1.0513E+10	1.32458E+10	10.12207695	Delta Pavonis (Evolved G - G7V-IV Star)	G7V-IV

1.000	1	1.168993	1.1690E+10	1.0000E+10	1.25893E+10	10.1	Sun	G2V
1.060	1.24	0.999300	9.9930E+09	8.5484E+09	1.08724E+10	10.03632538	51 Pegasi	G2-3 V
1.200	3.4	0.412586	4.1259E+09	3.5294E+09	7.95727E+09	9.900764149	Tau Boötis	F7 V
1.500	7.50	0.233799	2.3380E+09	2.0000E+09	4.53857E+09	9.656919174	Procyon A	F5 IV-V
1.670	4.10	0.476151	4.7615E+09	4.0732E+09	3.46418E+09	9.539600815	Algol C	A5 V
1.790	10.64	0.196637	1.9664E+09	1.6821E+09	2.90918E+09	9.463771203	Altair	A7 V
1.990	17.66	0.131727	1.3173E+09	1.1268E+09	2.22857E+09	9.348025889	Fomalhaut	A3 V
2.000	25.40	0.092047	9.2047E+08	7.8740E+08	2.20064E+09	9.342548325	Sirius	A1 V
2.300	38.00	0.080403	8.0403E+08	6.0526E+08	1.54818E+09	9.189820419	Vega	A0 V
3.600	98.00	0.048798	4.8798E+08	3.6735E+08	5.01455E+08	8.700231648	Algol A	B8 V
3.700	229.09	0.021455	2.1455E+08	1.6151E+08	4.68048E+08	8.670290822	Beta(2) Cygni - Alberio B	B8 Ve
6.950	2570.40	0.003592	3.5918E+07	2.7039E+07	9.58071E+07	7.981397835	r Centauri (HD 105937)	B3 V
10.000	16000.00	0.000830	8.3025E+06	6.2500E+06	3.83531E+07	7.5838	α(2) Crucis	B1 V
12.000	34673.69	0.000460	4.5974E+06	3.4608E+06	2.42418E+07	7.384564149	HD 216532	O8.5 V
13.000	57543.99	0.000300	3.0010E+06	2.2591E+06	1.98196E+07	7.297095737	ζ Oph	O9.5 V
13.000	30000.00	0.000576	5.7564E+06	4.3333E+06	1.98196E+07	7.297095737	σ Orionis B	O9.5 V
15.000	31168.00	0.000639	6.3931E+06	4.8126E+06	1.38267E+07	7.140719174	Mu Columbae	O9.5 V
17.000	32000.00	0.000706	7.0571E+06	5.3125E+06	1.00912E+07	7.003944424	AE Aurigae	O9.5 V
17.000	30199.52	0.000748	7.4779E+06	5.6292E+06	1.00912E+07	7.003944424	HD 216898	O8.5 V
18.000	35000.00	0.000683	6.8318E+06	5.1429E+06	8.73943E+06	6.941483323	σ Orionis A	O9.5 V
18.000	20000.00	0.001196	1.1956E+07	9.0000E+06	8.73943E+06	6.941483323	Pi Andromedae	B5 V
19.000	43651.58	0.000578	5.7821E+06	4.3526E+06	7.62782E+06	6.882400189	HD326329	O9 V
20.000	41686.94	0.000637	6.3732E+06	4.7977E+06	6.70422E+06	6.826348325	tau Scorpii	B0 V
25.000	151356.12	0.000219	2.1942E+06	1.6517E+06	3.82387E+06	6.58250335	Delta Orionis (A)	O9.5 II
26.000	91201.08	0.000379	3.7871E+06	2.8508E+06	3.46453E+06	6.539644062	HD 66788	O8.5 V
30.000	158489.32	0.000251	2.5145E+06	1.8929E+06	2.41695E+06	6.383267499	HD 96715	O4 V
40.000	371535.23	0.000143	1.4302E+06	1.0766E+06	1.17192E+06	6.06889665	Zeta Puppis (Blue Supergiant)	O5 IAf
45.000	251000.00	0.000238	2.3816E+06	1.7928E+06	8.71338E+05	5.940186673	Theta¹ Orionis C	O7 V
57.000	501187.23	0.000151	1.5108E+06	1.1373E+06	4.80693E+05	5.681867688	HD 64568	O3 V
85.000	1013911.39	0.000111	1.1136E+06	8.3834E+05	1.75872E+05	5.245196099		
92.000	6300000.00	0.000022	2.2018E+05	1.4603E+05	1.44118E+05	5.158717069	Cygnus OB2-12	
120.000	5000000.00	0.000036	3.6187E+05	2.4000E+05	7.38523E+04	4.868364149	Eta Carinae	Peculiar

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