FORMATION AND EVOLUTION OF COMPACT BINARY SYSTEMS

- Main Categories of Compact Systems
- Formation of Compact Objects
- Mass and Angular Momentum Loss
- Evolutionary Links to Classes of Binary Systems
- Future Work

Main Categories of Compact Binary Systems

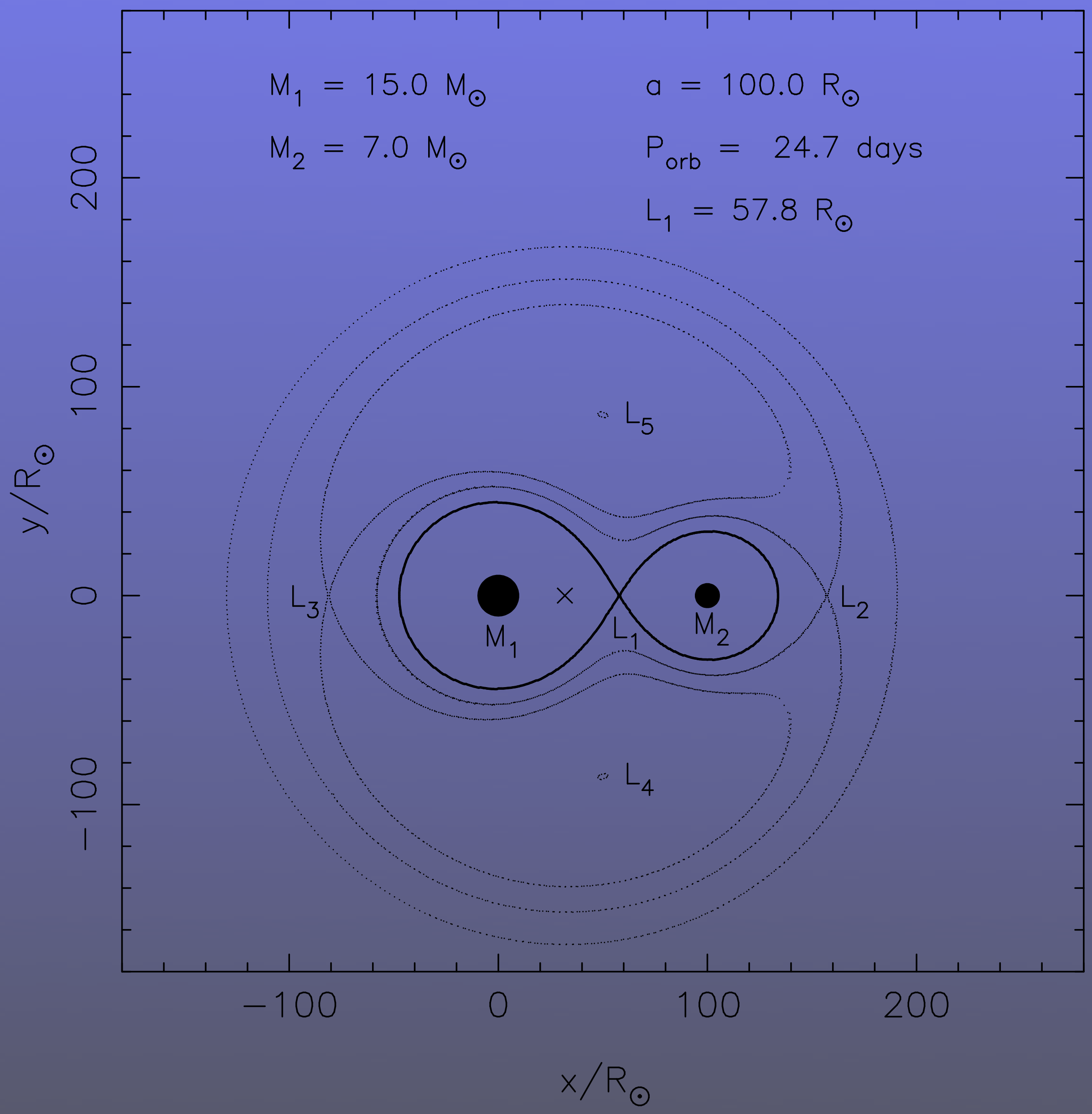
- Stellar Binary X-ray Sources (Black Holes/ Neutron Stars with a Companion) - strong X-ray sources in galaxies
- Binary Radio Pulsars (Neutron Star/Neutron Star or Neutron Star/White Dwarf Star) - important sources of gravitational radiation

- Cataclysmic Variables (White Dwarf Star with a Companion) - possible progenitors for Type Ia supernovae: probes of the curvature of the universe
- Significant Mass and/or Angular Momentum Removed from the System - binary interaction, stellar winds, supernova explosions

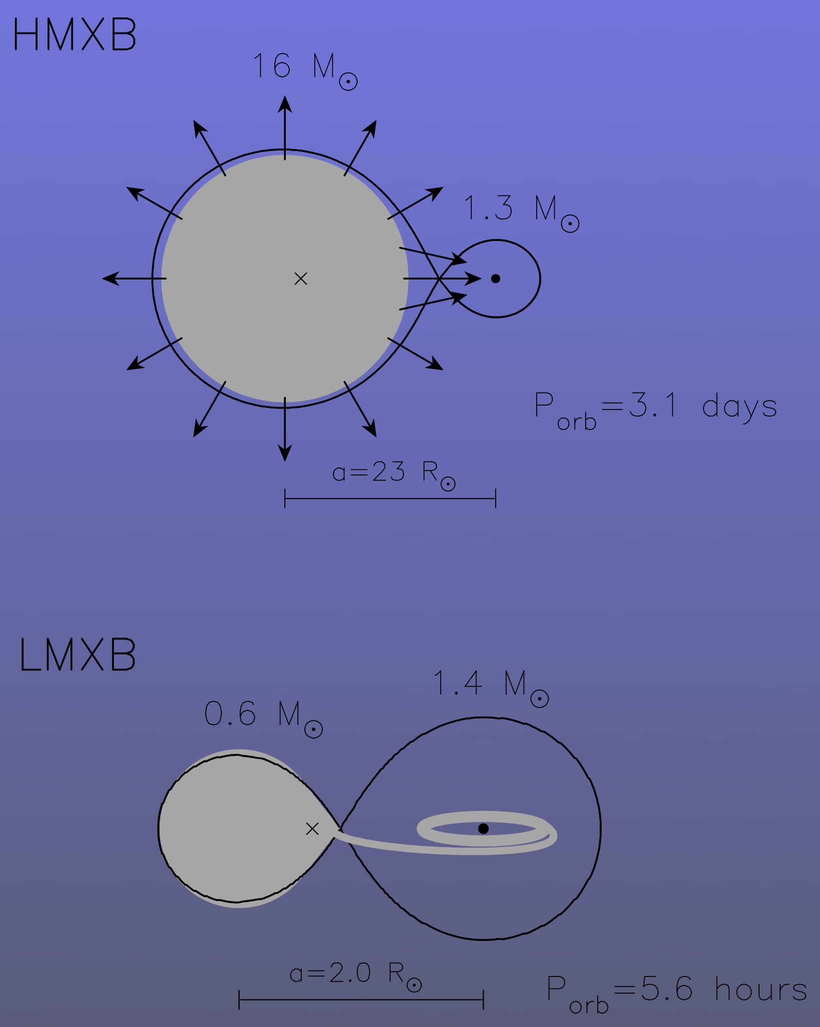
MAIN CLASSES OF X-RAY BINARY SOURCES

	HMXB	LMXB
X-ray Spectra	Hard (>10 keV)	Soft (<10 keV)
Accreting Star	High B field NS (or BH)	Low B field NS (or BH)
Accretion Process	Wind	Roche lobe overflow
Companion Star	High Mass	Low Mass

Roche Geometry



Examples of Typical Binary X-ray Sources



CATACLYSMIC VARIABLE BINARIES

Nova-like Systems	Donor less massive than WD	Porb ~ several hours
Supersoft Sources	Donor more massive than WD	Porb ~ hours to days
Double compact pair	WD/WD	Porb as short as 10 minutes

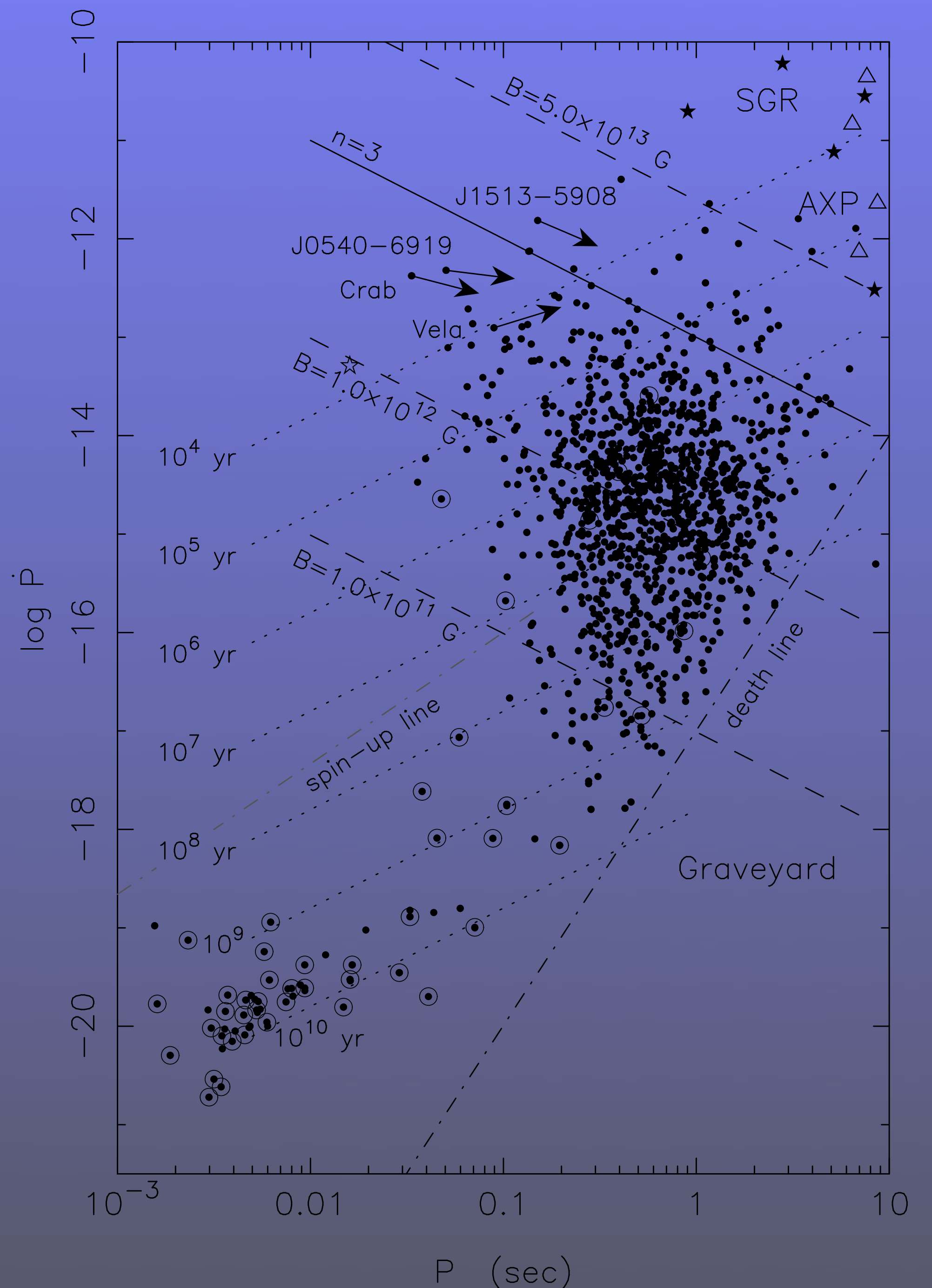
ACCRETION ENERGETIC EFFICIENCIES

Star	Radius (km)	GM/Rc^2
Sun	700,000	0.000002
White Dwarf	10,000	0.0002
Neutron Star	10	0.15
Black Hole	3	0.1 - 0.4

BINARY RADIO PULSARS

High Mass Companion	NS/NS NS/WD	7.5 hours 1.35 days
Low Mass Companion	NS/WD	175 days
Unevolved Companion	Noncompact	3.4 years

RADIO PULSAR DIAGRAM



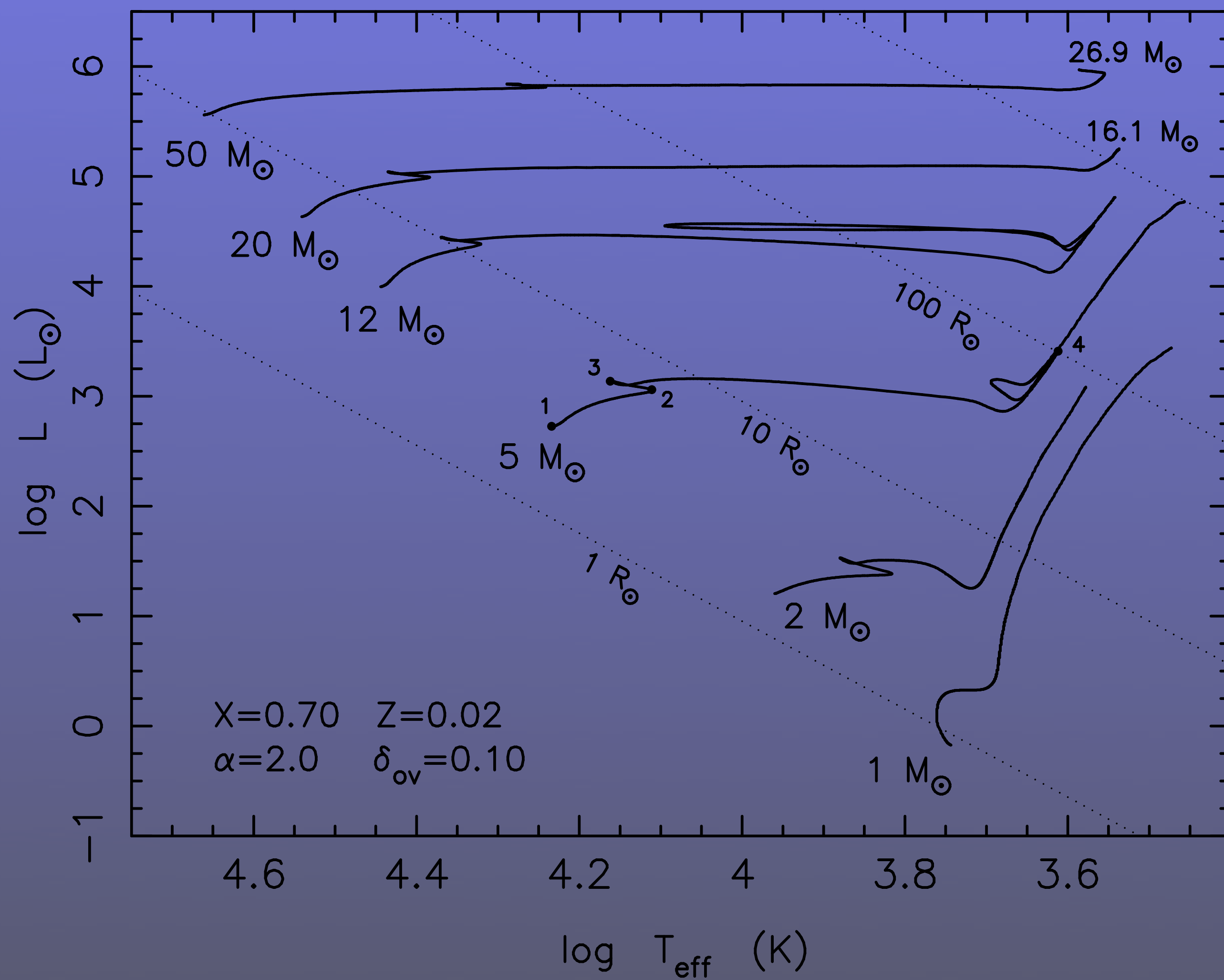
FORMATION OF COMPACT OBJECTS I.

- For progenitor masses less than about 8-12 solar masses, white dwarfs form as a result of the removal of stellar envelope due to wind mass loss or mass transfer leaving behind an electron degenerate core
- For progenitor masses between 12-25 solar masses, neutron stars form by the core collapse of massive stars; for masses between 8-12 solar masses formation of neutron stars in binaries by accretion induced collapse of ONeMg white dwarfs is possible

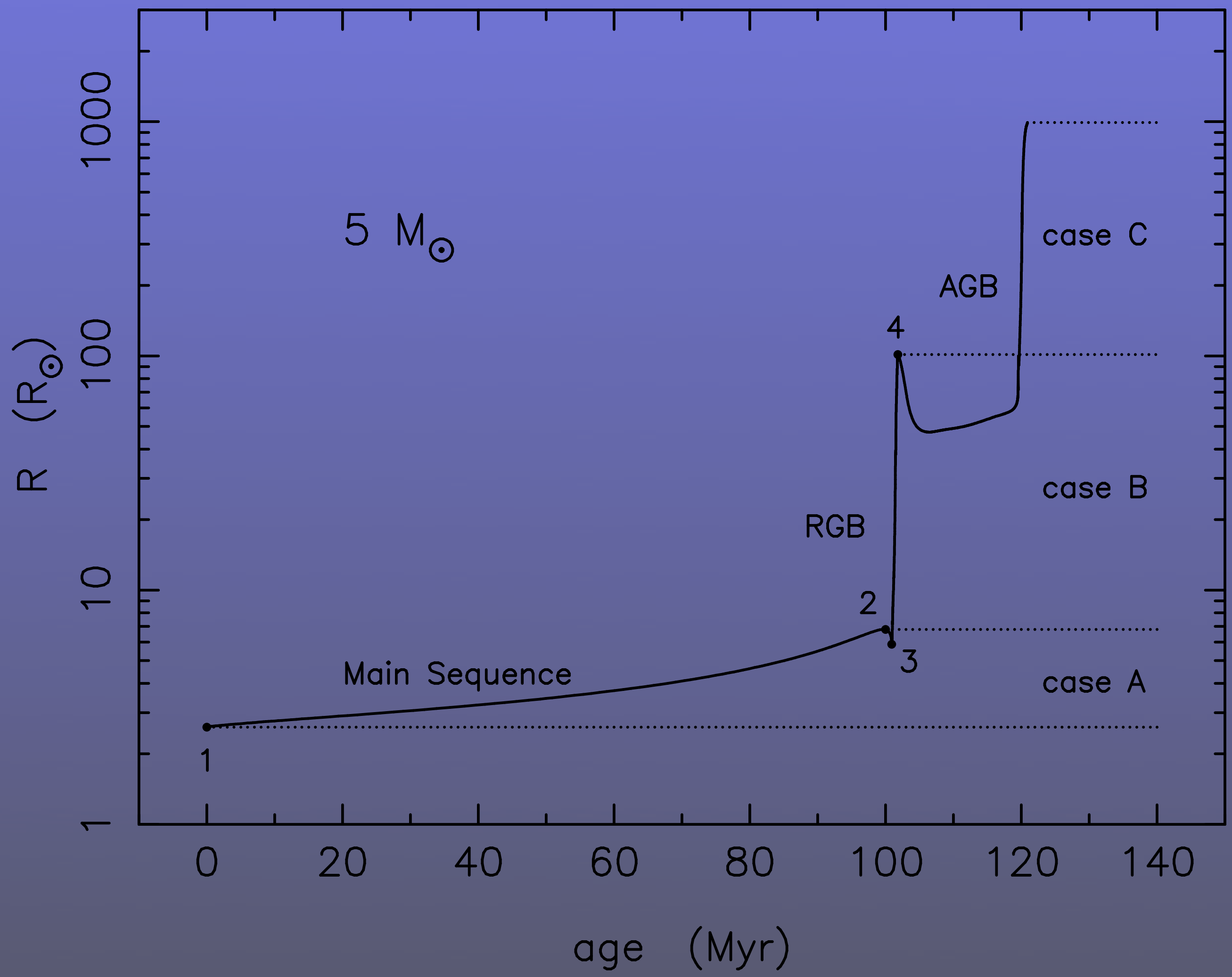
FORMATION OF COMPACT OBJECTS II.

- For progenitor masses greater than about 25 solar masses, black hole formation is likely
- Black hole formation via accretion induced collapse of a neutron star in a binary star system

Stellar Evolutionary Tracks



Temporal Evolution of Stellar Radius



Need for Angular Momentum Loss

- The specific angular momentum of the observed systems is much less than the specific angular momentum of the progenitor system
- To produce a compact object, the stellar radius of the evolved progenitor star is much larger than the current orbital separation of the system

MASS TRANSFER PRELIMINARIES

- Orbital Evolution

$$J^2 = \frac{GM_1^2 M_2^2 a}{M_1 + M_2}$$

$$\frac{\dot{a}}{a} = \frac{2\dot{J}}{J} - \frac{2\dot{M}_1}{M_1} - \frac{2\dot{M}_2}{M_2} + \frac{\dot{M}_1 + \dot{M}_2}{M_1 + M_2}$$

Now if $\dot{M}_1 = -\dot{M}_2 < 0$

$$\frac{\dot{a}}{a} = \frac{2\dot{J}}{J} + \frac{2\dot{M}_1(M_1 - M_2)}{M_1 M_2}$$

Mass transfer from more to less massive star shrinks binary and vice versa

ROCHE LOBE CONSTRAINT ON STELLAR RADIUS

- Roche lobe condition for a binary with mass ratio q

$$R_{lobe} = \frac{0.49q^{2/3}a}{0.6q^{2/3} + ln(1 + q^{1/3})}$$

MASS AND ANGULAR MOMENTUM LOSS DURING FORMATION PHASE

- Crucial stage for transforming a long period progenitor system (required to incubate the compact object) involves a common envelope phase of evolution - binary departs from synchronous rotation resulting in a tidal instability and unstable mass transfer

EVOLUTION TO THE COMMON ENVELOPE STAGE - ONSET OF SPIRAL-IN PHASE

1. Tidal Instability - Moment of Inertia of giant is >1/3 moment of inertia of binary
2. Unstable Mass Transfer - Mass transfer time scale is shorter than the thermal time scale of the accreting component

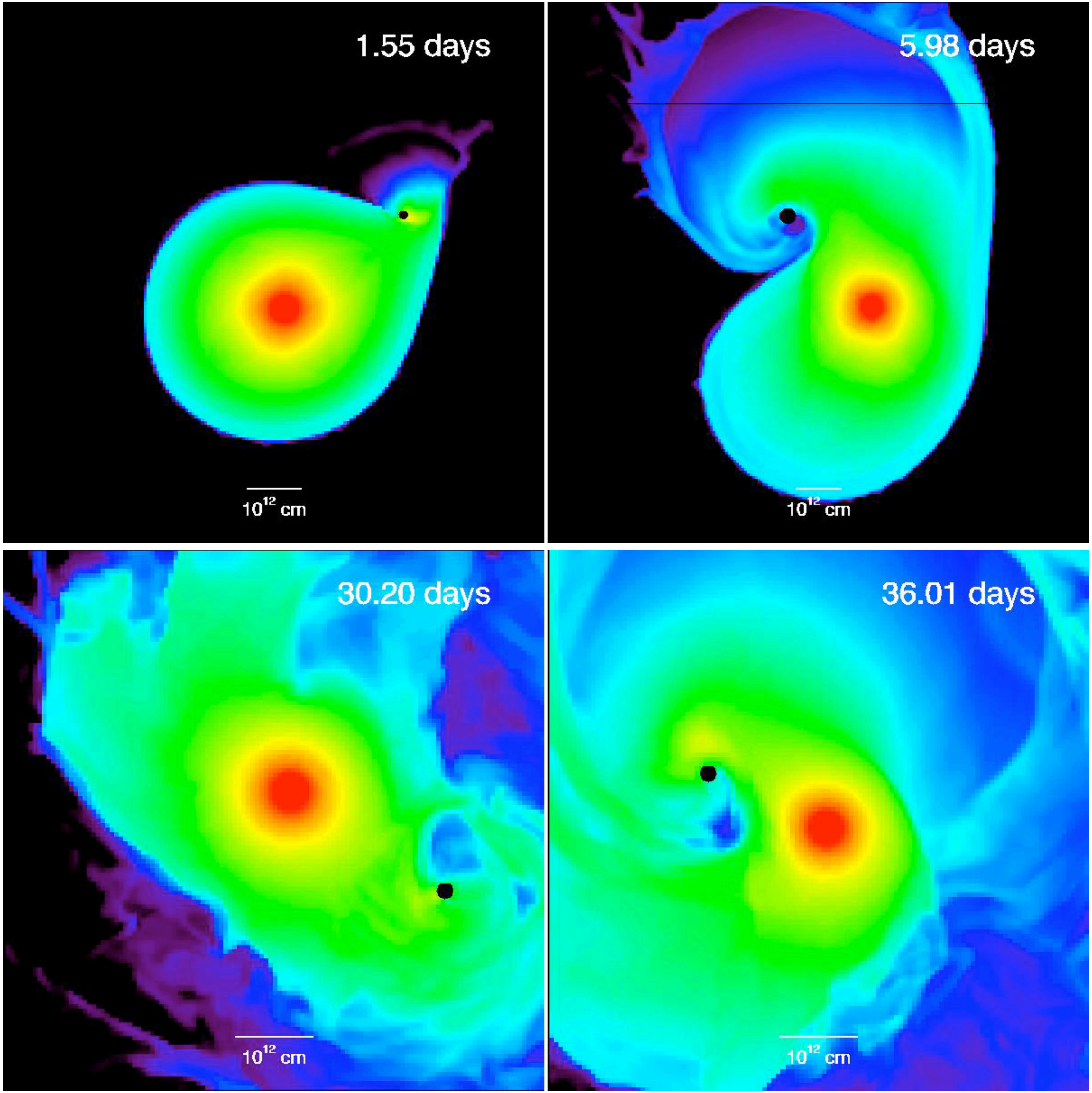
Common envelope evolution occurs for large mass ratios and/or where the primary develops a deep convective envelope before filling its Roche lobe

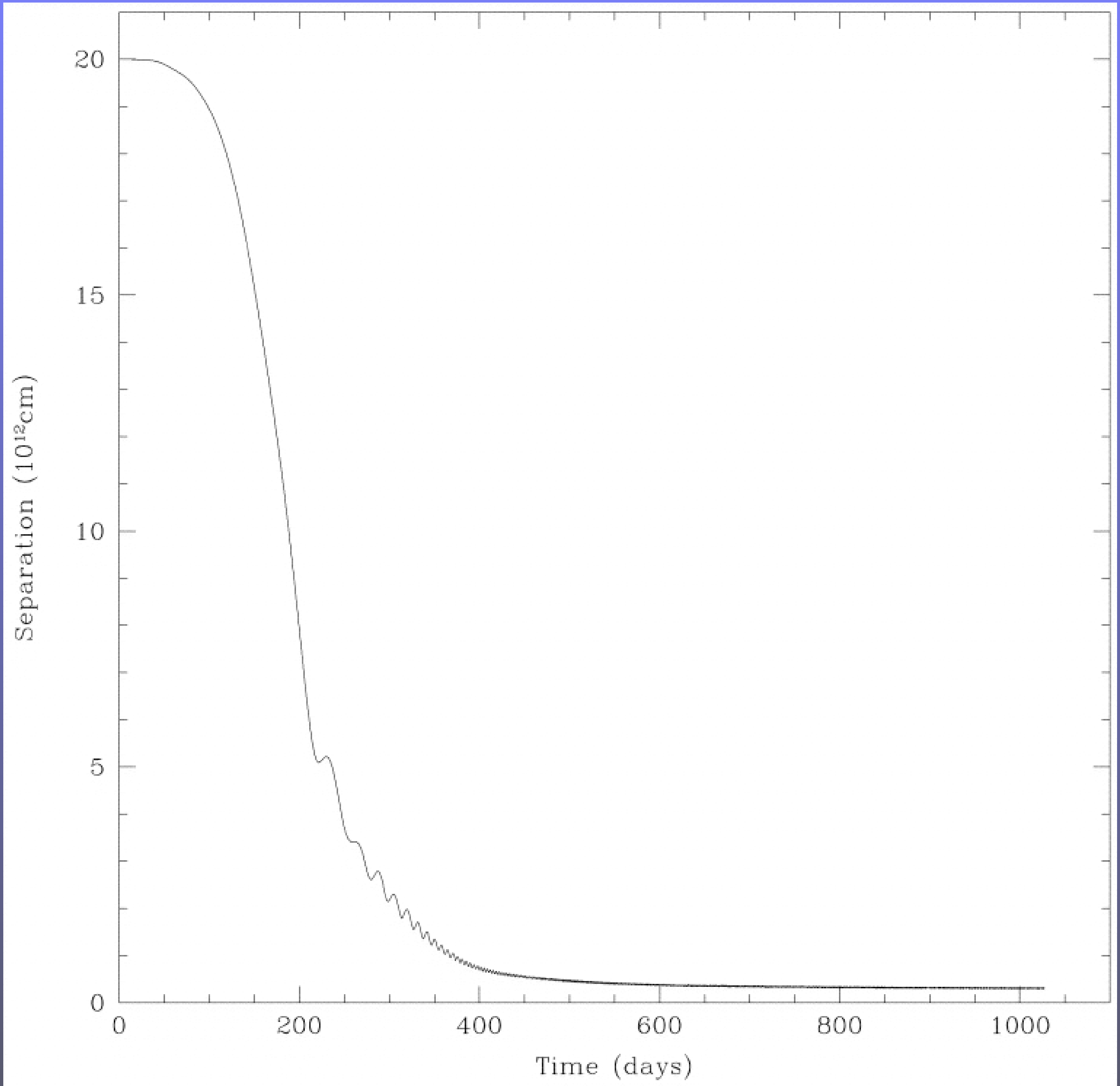
Formation of a Short Period Compact Binary System: General Conditions for Ejection of the Common Envelope

1. Energy released from the orbit is greater than the binding energy of the envelope from the binary.

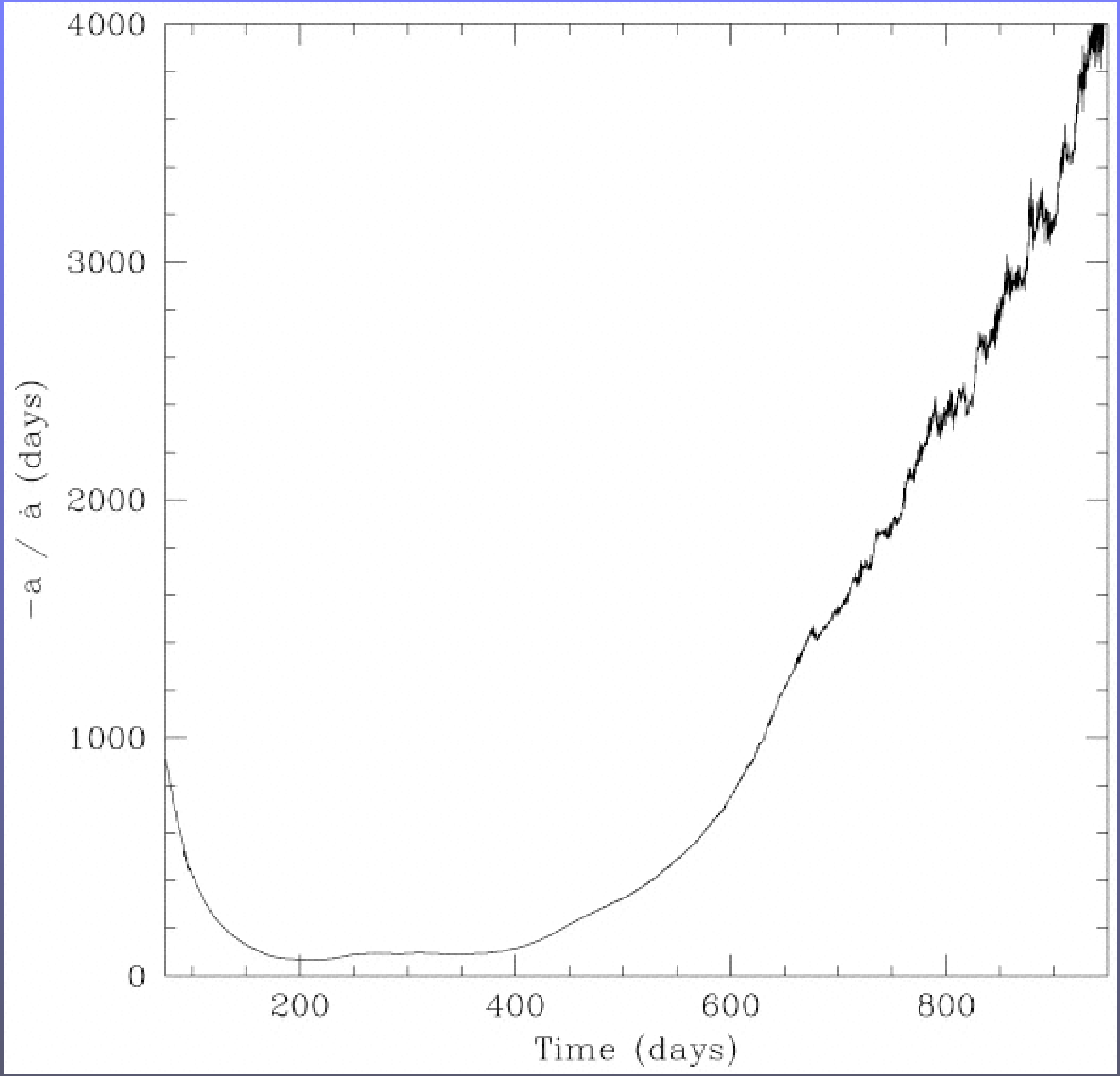
2. Time scale for energy loss from the binary orbit is less than the energy transport time scale.

3. Ejection time scale is shorter than the spiral decay time scale.


1.55 days
10^{12} cm
5.98 days
10^{12} cm
30.20 days
10^{12} cm
36.01 days
10^{12} cm



20
15
10
5
0
Separation (10^12cm)
0
200
400
600
800
1000
Time (days)



4000
3000
2000
1000
0
-a / ȧ (days)
200
400
600
800
Time (days)

Summary of 3D Results

1. Orbital decay is rapid (~ dynamical timescale)

2. Relative orbit is initially eccentric and circularizes as the orbital separation shrinks

3. Mass is ejected in all directions with a preference for mass loss in the orbital plane.

4. Efficiency of the mass ejection process < 40% - 50%

5. Evidence for spin up of gas surrounding the cores

6. Termination of common envelope phase is facilitated by progenitor stars with steep density gradients above the core and where the mass of the common envelope is comparable to the mass of the inspiralling companion

EVOLUTIONARY LINKS TO CLASSES OF SYSTEMS

- Cataclysmic Variables - successful ejection of common envelope and survival of a remnant binary is favored on the red giant and asymptotic giant branch: orbit significantly shrinks (more than a factor of 100) and can lead to double degenerate systems and Type Ia supernovae

- LMXBs - successful ejection of the common envelope and survival of a remnant binary is favored for the late core helium burning phase and beyond: systems can lead to the binary millisecond pulsar phase
- HMXBs - same as above, but these systems lead to the formation of binary radio pulsars with a compact neutron star or white dwarf companion

EVOLUTION OF COMPACT BINARY SYSTEMS

- Nuclear evolution dominant - intermediate to massive donors
- Angular momentum loss dominant (magnetic braking, gravitational radiation) - low mass donors at short orbital periods

BINARY MILLISECOND PULSARS

- Neutron star is spun up by the accretion of matter via an accretion disk to millisecond spin periods - “recycled pulsar” is the endpoint of LMXBs
- Mass transfer from donor to neutron star may be either driven by nuclear evolution (long orbital periods ~ months) or by angular momentum losses (short orbital periods ~ hours)

PULSAR SPIN UP

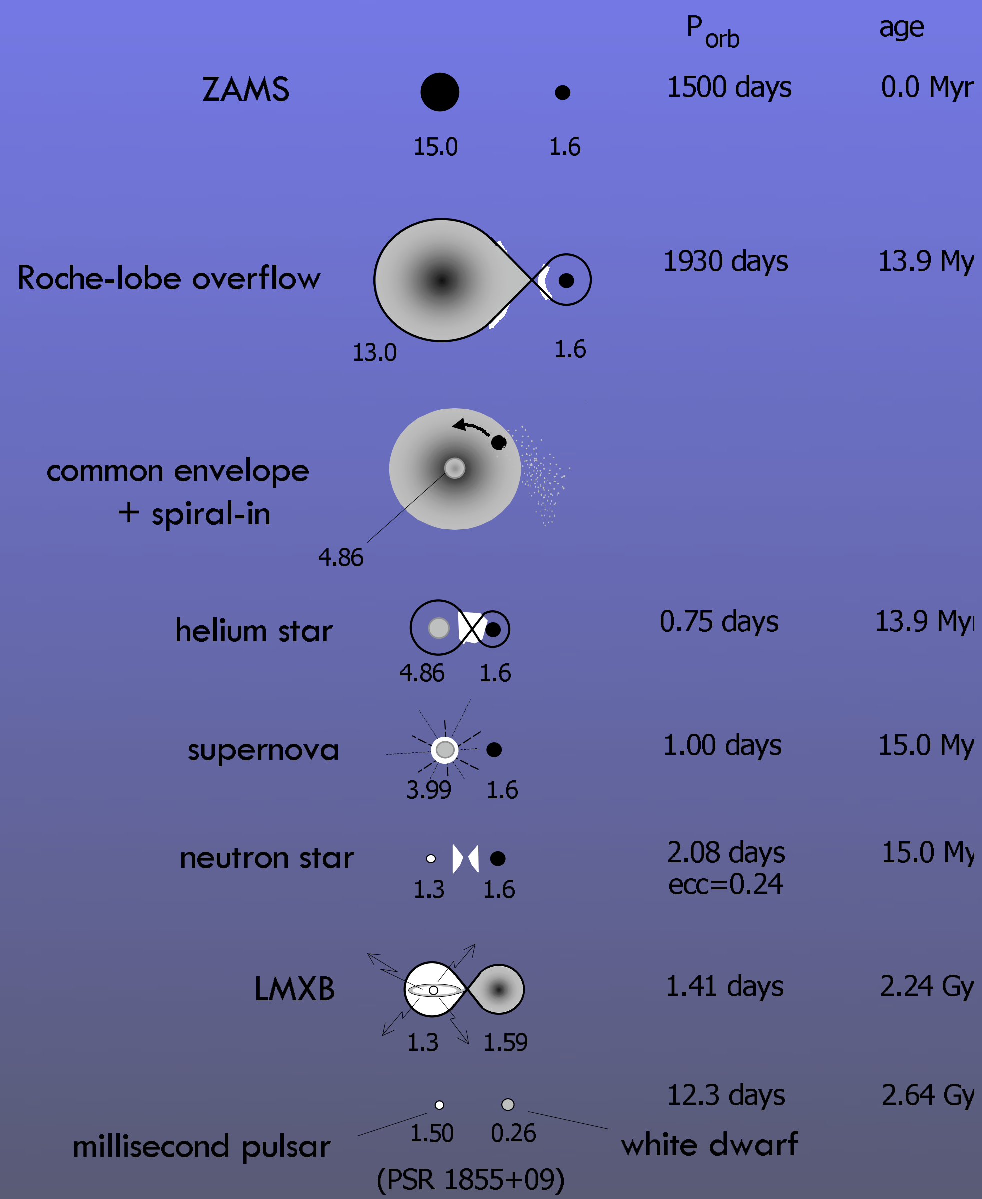
Recycling: $\Omega_{equilibrium} = \Omega_{Kepler}(r = R_{Mag})$

$$P_{eq} = 2.4 B_9^{6/7} M^{-5/7} \left(\dot{M} / \dot{M}_{\mathrm{Edd}} \right)^{-3/7} R_6^{16/7}$$

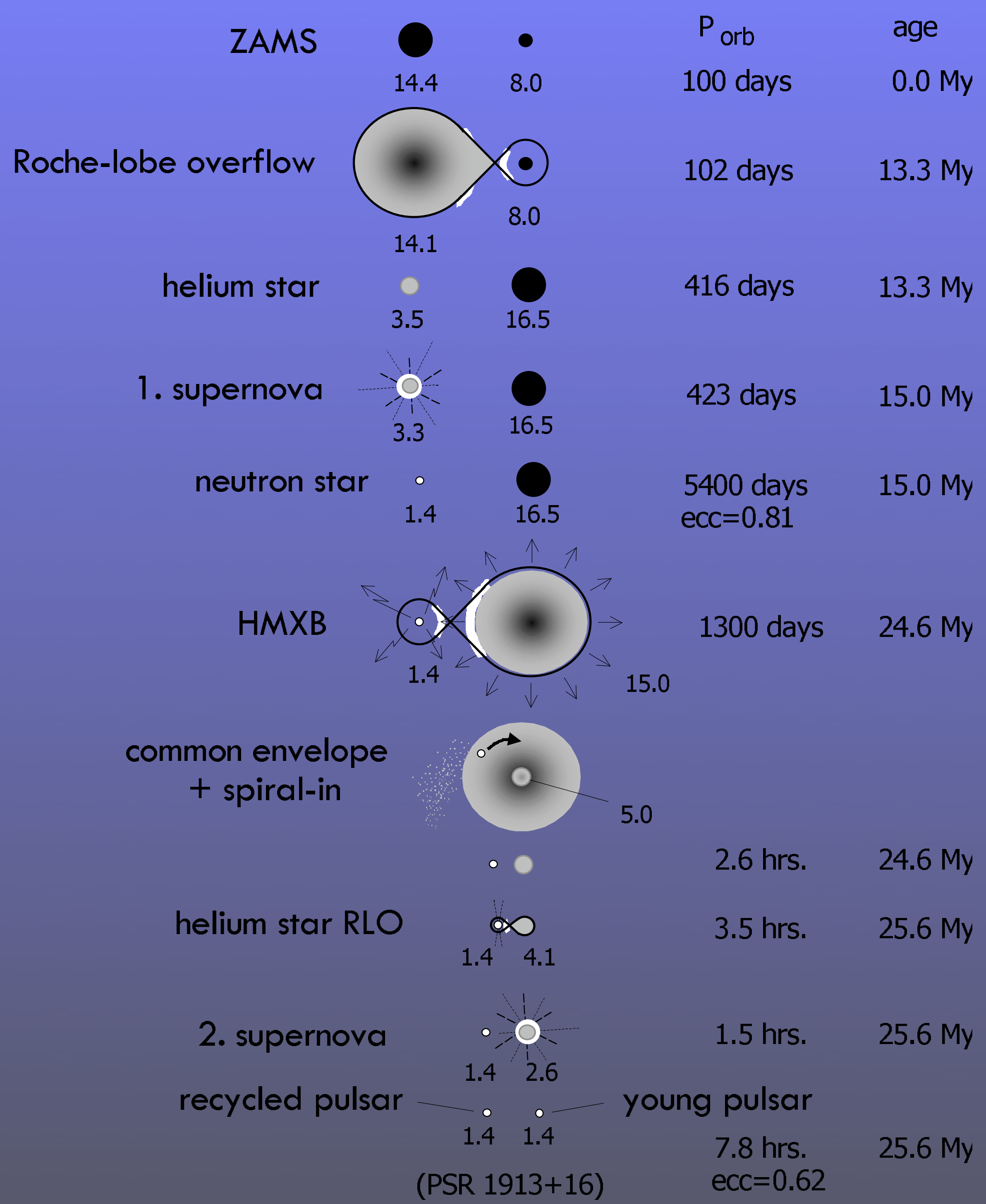
where $\dot{M}_{\mathrm{Edd}} = 1.5 \times 10^{-8} R_6 M_\odot yr^{-1}$

$P_{eq} = 1.9 B_9^{6/7}$ ms

Binary Evolutionary History of a LMXB



Binary Evolutionary Track of HMXB



FUTURE WORK

1. Determine efficiency of common envelope phase

$$\alpha_{CE} = f(M_1, M_2, P_{orb})$$

to delineate the regimes where a post spiral in system survives and where the system merges

2. Provide input for population synthesis modeling to determine the birth rates for the formation of compact systems for cosmology (Type Ia supernova evolutionary channels) and gravitational wave astronomy (neutron star mergers)