Ultracompact binaries

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Collaboration:
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Ultracompact Binaries

Stellar binaries with degenerate primary and secondary star

- White dwarf
  - Detached
  - Semi-detached: AM CVn stars
  + WD
  + NS

- Neutron Star
  - Detached WD+NS systems: WD+pulsar
  - Semi-detached: Ultracompact X-ray binary
  + WD
  + NS
  + BH

- Black Hole
  + WD
  + NS
  + BH

Short period systems: $P_{\text{orbital}} < \text{few hrs}$
Intrinsically rare! Observationally rare!
Astrophysical Interest

• Endpoints of binary evolution: common-envelope physics

• Gravitational wave sources: LISA/LIGO domain

• Accretion disk & Jet physics:
  - Chemical composition
  - AGN connection

• Explosive phenomena
  - Dwarf novae outburst
  - Nova outbursts
  - Supernovae Type Ia
  - Supernovae Type Ia
  - (Short) Gamma-ray bursts
Number of AM CVn stars

AM CVn System Discoveries

# of AM CVn Systems Known

Year


AM CVn
CR Boo
GP Com
SDSS
PTF

Courtesy David Levitan
AM CVn stars: An evolutionary challenge

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AM CVn stars

- Interacting binary white dwarfs
- Completely hydrogen deficient
- Orbital periods: 5.4-65 minutes
- Only 32 systems known
- Only known LISA sources
- Ultimate survivors: 2 x CE phase + Direct impact phase
- Evolution fully (?) set by GWR losses

\[
\frac{\dot{J}}{J} = -\frac{32}{5} \frac{G^3}{c^5} \frac{M_1 M_2 (M_1 + M_2)}{a^4}
\]

\[
\frac{\dot{M}_2}{M_2} = \frac{\dot{J}}{J} \frac{2}{\zeta_2 + 5/3 - 2q}
\]
Evolutionary paths

Gravitational wave evolution

Orbital Period (log s)

Gravitational wave strength

Post CE-system

Detached

LISA visible

LISA invisible

AM CVn

RLOF

Merger SN Ia?
Gravitational wave evolution

- Nelemans et al., 2004
- Roelofs et al., 2006
- Hils & Bender, 2000

![Graph showing gravitational wave evolution](graph.png)

- AM CVn systems
- UC X-ray binaries
- Double WD/ sdB + WD

LISA 5σ limit at T=1yr

Nelemans et al., 2004
Roelofs et al., 2006
Hils & Bender, 2000
Galactic population in Gravitational waves

Nelemans, Yungelson & Portegies Zwart, 2004
Follow the evolution:

Start at 'first contact': at shortest orbital periods

Move out to longer periods.
Direct impact phase

At first contact between 2 white dwarfs: separation so small that direct impact occurs

\[ P_{\text{orb}} \leq 10 \text{ min} \ (\text{HM Cnc, V407 Vul}) \]

Stability depends on synchronization timescale of spin-orbit coupling:

short = stable 
long = unstable

Marsh, Nelemans, Steeghs, 2004
Nelemans et al., 2001
Webbink, 1984
Smarr & Blandford, 1976
Campbell, 1984
Direct impact phase

*And* on degeneracy (entropy) of the donor star at start of mass transfer

\[ \log \frac{E_{F,c}}{kT_c} = \text{“(degeneracy/thermal)”} = 2.0, 4.0 \]

High entropy = More stable

Low entropy = Less stable

Roelofs and Deloye, 2010, in prep.
Deloye, Taam et al, 2007
HM Cnc & V407 Vul

- Detected as soft X-ray sources with ROSAT (Motch et al. 1996; Israel et al. 1999)
- X-ray and optical photometric period of 321s & 569s
- These are also only detected periods
- Period is currently decreasing at $1 \times 10^{-17}$ and $3 \times 10^{-16}$ s s$^{-1}$ (Strohmayer 2005)
- Optically faint: $V=19.9$ (V407 Vul) and $V=21.1$ (HM Cnc)

Barros et al., 2007
Three models

Intermediated polar

Motch/Isreal/Norton et al.

Direct impact

Wu/Dall’Osso et al.

Period is not orbital but spin

→ What is orbital period?

→ What causes phase lag?

No transfer, period is orbital

→ Phase lag? Emission lines?

→ Physics? Slipping footpoints?

Mass transfer, period is orbital

→ Decreasing orbital period?

→ Presence hydrogen?

Radial velocity changes needed to set orbital period

Three models
**HM Cnc: radial velocity changes**

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**Difficult!**

- HM Cnc is faint \( (V = 21.1) \)
- Need to resolve orbital motion \( (T_{\text{int}} < 1 \text{ min}) \)
- Emission lines are weak \( (< 10\%) \)

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**Could only be done on Keck +LRIS**

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Hydrogen, not Hel}
HM Cnc: $P_{\text{orb}} = 5.4 \text{ min}$

System just started mass transfer:

Will most likely merge
(Roelofs & Deloye, 2010)

\[ M_1 = 0.55 \, M_{\text{sun}} \]
\[ M_2 = 0.27 \, M_{\text{sun}} \]
Helium (super)novae

Helium supernova (Type Ia)
Fusion on dynamical timescale

Evolution
AM CVn star

Log \( t \)

Log \( M_{\text{dot}} \)

Log \( L \)
First helium nova: V445 Puppis
Supernovae Type Ia ('point Ia')

Thermonuclear flashes in high state systems: $L \sim 0.1 \ L_{\text{SN}Ia}$,
$\tau \sim 0.1 \ \tau_{\text{SN}Ia}$, $f = 0.1 \ f_{\text{SN}Ia}$

Bildsten et al., 2007
Shen et al., 2009, 2011

SN2002bj: SN Ia?
Poznanski et al., 2009

SN2010X: PTF discovery
Kasliwal et al., 2010
Intermediate period systems

- $10 \text{ min} < P_{\text{orb}} < 20 \text{ min}$: Three systems in high, stable $\dot{M}$ state (AM CVn, HP Lib)

- $20 \text{ min} < P_{\text{orb}} < 40 \text{ min}$: Ten systems showing DN-type outbursts (4 found in PTF within 1 year!)

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![Graph showing spectral data for SDSS J1240-01 and SN 2003aw, comparing flux in erg cm$^{-2}$ s$^{-1}$ Å with log($R_2/R_0$). The graph includes labels for different models and astronomical objects such as GP Com, SN 2003aw, and degenerate models.](image-url)
First eclipsing system: SDSSJ 0926+38

$P_{\text{orb}} = 28 \text{ min}$

Copperwheat et al., 2010
Long period systems from SDSS (>35min)

Thirteen systems found in SDSS photometry/spectroscopy (Roelofs et al., 2005; Anderson et al., 2005; 2008; Roelofs et al., 2009; Rau et al., 2010)

Space density: $2 \times 10^{-6} \text{ pc}^{-3}$ (…seems to be even lower) (Roelofs, Nelemans & Groot, 2007)
Observational/Theoretical questions

Five major outstanding, theory related, questions
Observational/Theoretical questions: I

What is the 'real' orbital period distribution?

- SDSS Follow-up: 5 long period systems instead of 25
- PTF: already 4 shorter period systems without trying.. (work by David Levitan)
- Kepler: A 15-minute system in 100 sq.degr.: what are the odds?

All seems to point at steeper orbital period profile:

More at shorter periods, fewer at longer.
- Extra angular momentum loss over GR (winds, braking)?
- Influence of chemical evolution Galaxy?
- Age of the Galaxy?
- Destruction/Decoupling at long periods?
Observational/Theoretical questions: II

What happens during direct impact?

Stable

Unstable

$M_{\text{tot}} < M_{\text{ch}}$

Unstable

$M_{\text{tot}} > M_{\text{ch}}$

AM CVn

Single WD

SN Ia
Observational/Theoretical questions: III

Which evolutionary channel dominates/exists/contributes?

- Determine $M_{\text{dot}}$ at a given $P_{\text{orb}}$:
  Difficult, requires distances (Roelofs et al., 2006)

- Determine abundances of the secondary!

![Graphs showing abundances of C, O, Ne, N for 0.2 $M_{\odot}$ WD and 0.45 $M_{\odot}$ He*](image-url)
Observational/Theoretical questions: IV

How do we translate abundances into spectra and vice versa?

- Stability of disk models at low $M_{\text{dot}}$
- Vertical structure of the disk?
Observational/Theoretical questions: IV

Precursors! Which, where, what, how

WD Channel: Low mass WD binaries found in SDSS,
- SDSS J1257+5428 (Marsh et al., 2010; Kulkarni & Van Kerkwijk, 2010)
- SDSS J1436+5010 & SDSSJ1053+5200 (Mullaly et al. 2010)
- Short period systems by Kilic et al., 2011 (48, 40 and 12(!) minutes)

Evolved CV Channel: Short period, high He-content CVs
- V485 Cen; $P_{\text{orb}} = 59$ min; EI Psc, $P_{\text{orb}} = 64$ min
- SDSS J1111+57

Helium Channel: sdB+WD systems
- GALEX 2349+3844 (Kawka et al. 2010)
- NLTT 11748 & 54331 (Kawka et al., 2010)
Pre-cursor systems

All Sloan Cataclysmic Variables & AM CVn systems

SDSSJ1111+57

SDSSJ0932+47

AM CVn

CVs

EW(Hα)/EW(HeI)=2.5
Open questions

Only 32 systems known (but increasing rapidly)

- Formation channel? Abundances! (Nelemans, Yungelson et al., 2010)
  Disk modeling (e.g. Nagel et al., 2010)

- Space density? Population characteristics?
- Gravitational wave sources/LISA Population:

Large-scale (variability) surveys: EGAPS, Omegawhite, PTF, etc.

- Connection to SN Ia, SN Ia, helium novae?

Variability surveys (see above)

Theory: physics of direct impact, synchronization, accretion disk physics, common-envelope physics
Thanks!

I'll be at Caltech until the end of 2011
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Radboud University Nijmegen
The Universe is talking. We are listening

Free format after NASA/ESA LISA poster
Astrophysics in Nijmegen

- Compact objects and binaries:
  White dwarfs, neutron stars and (supermassive) black holes

- Astroparticle physics:
  Ultra-high energy cosmic rays and gravitational waves