Angular Momentum and Stability: Double White Dwarfs as Progenitors of AM CVn

Jeremy F. Sepinsky
The University of Scranton

Kyle Kremer & Vassiliki Kalogera
Northwestern University & CIERA

Third International Workshop on AM CVn stars
April 16–20, 2012

Outline

Outline

Background

Motivation

Exploring the possibility of Double White Dwarfs as a formation channel for AM CVn

Problems

- Double White Dwarfs (DWDs) are small enough and H-poor enough, but the mass transfer (MT) process does not appear to be dynamically stable
- A fact which largely amounts to angular momentum losses during MT

Background

An (incomplete) history of the DWD formation channel

Paczynski (1967)

Suggests semi-detached dwarfs can explain the newly discovered AM CVn

Pringle & Webbink (1975), Tutukov & Yungleson (1979)

Examine gravitational radiation as a method to induce MT in close binaries

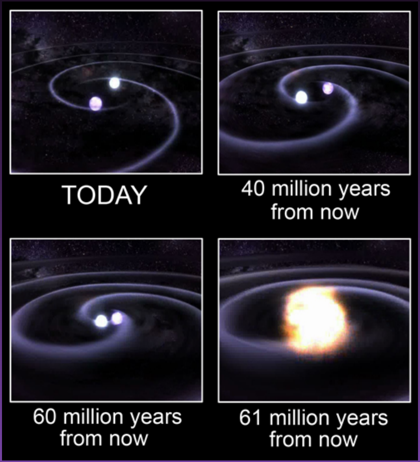


Image credit: NASA/GSFC/D.Berry

Eventually MT Occurs

Gravitational waves decrease $J_{\rm orb}$

$J_{\rm orb}$ directly affects the separation, a

$$J_{\rm orb} = \left(\frac{Ga}{M_D + M_A}\right)^{1/2} M_D M_A$$

$$\frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = (1-q)\frac{\dot{M}_D}{M_D} + \frac{1}{2}\frac{\dot{a}}{a}$$

Since $R_L \propto a$ and $R_D \propto M_D$, mass transfer is stable only if

Stability Criterion*

$$q < \frac{5}{6} + \frac{\zeta(M_D)}{2}$$

Where $\zeta(M_D) = d\log R_L / d\log M_D \approx -1/3$

* Assumes all J from stream returned to the orbit

Background, cont'd

Skipping a few years. . .

Nelemans et al. (2001)

- Noted that for DWD, the accretor is large compared to the binary separation
- Ballistic trajectories of Lubow & Shu (1975) would cause direct impact of the stream onto the accretor
- No disk means its harder to return angular momentum (J) back to the orbit.
  $J_{\rm stream} \rightarrow J_{\rm Spin,A}$

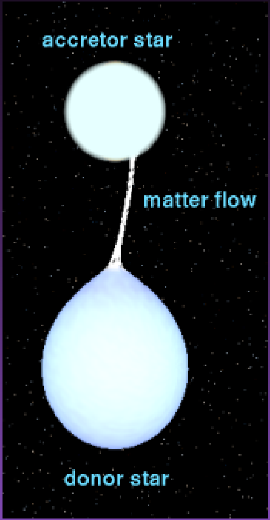


Image credit Andrzej Krolak via einstein-online.info

This is a problem because. . .

see, e.g., Nelemans et al. (2001); Marsh, Nelemans, and Steeghs (2004)

$J_{\rm orb}$ directly affects the separation, a

$$J_{\rm orb} = \left(\frac{Ga}{M_D + M_A}\right)^{1/2} M_D M_A$$

$$\frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = (1-q)\frac{\dot{M}_D}{M_D} + \frac{1}{2}\frac{\dot{a}}{a}$$

Since $R_L \propto a$ and $R_D \propto M_D$, mass transfer is stable only if

Stability Criterion*

$$q < \frac{5}{6} + \frac{\zeta(M_D)}{2} + f(J_{stream})$$

* Assumes the average J of a ballistic particle is removed from the orbit.

This is a problem because. . .

see, e.g., Nelemans et al. (2001); Marsh, Nelemans, and Steeghs (2004)

$J_{\rm orb}$ directly affects the separation, a

$$J_{\rm orb} = \left(\frac{Ga}{M_D + M_A}\right)^{1/2} M_D M_A$$

$$\frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = (1-q)\frac{\dot{M}_D}{M_D} + \frac{1}{2}\frac{\dot{a}}{a}$$

Since $R_L \propto a$ and $R_D \propto M_D$, mass transfer is stable only if

Stability Criterion*

$$q < \frac{5}{6} + \frac{\zeta(M_D)}{2} - \sqrt{(1+q)r_h}$$

* Assumes the average J of a ballistic particle is removed from the orbit. (r_h from Lubow & Shu (1975) ; Verbunt & Rappaport (1988))

But now we have tides

Marsh, Nelemans, and Steeghs (2004)

Tides return J to the orbit from the accretor on a timescale τ_A

$$\dot{J}_{\rm tides,A} = \frac{kM_A R_A^2}{\tau_A}(\Omega_A - \Omega_{\rm orb})$$

So our orbital angular momentum changes like

Angular Momentum Balance

$$\dot{J}_{\rm orb} = \dot{J}_{GW} + \dot{J}_{MT} + \dot{J}_{\rm tides}$$

But now we have tides

Marsh, Nelemans, and Steeghs (2004)

Tides return J to the orbit from the accretor on a timescale τ_A

$$\dot{J}_{\rm tides,A} = \frac{kM_AR_A^2}{\tau_A}(\Omega_A - \Omega_{\rm orb})$$

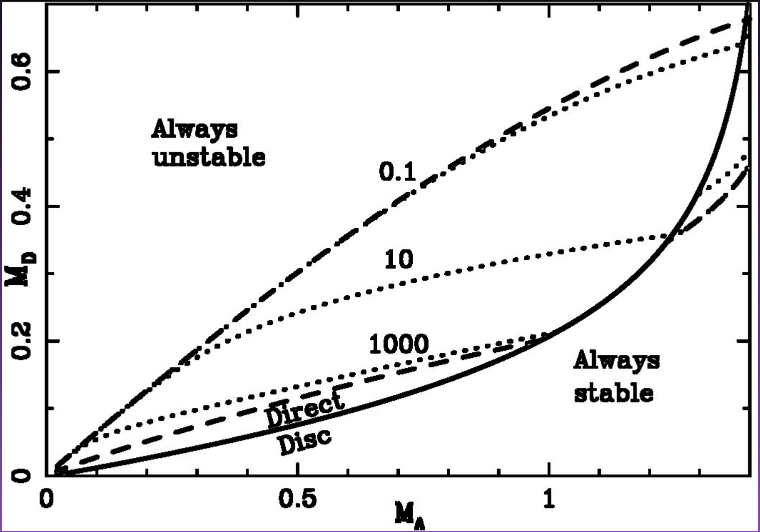
So our orbital angular momentum changes like

Angular Momentum Balance

$$\dot{J}_{\rm orb} = \dot{J}_{GW} + \sqrt{GM_Ar_ha}\dot{M}_D + \frac{kM_AR_A^2}{\tau_A}(\Omega_A - \Omega_{\rm orb})$$

White Dwarf Stability

Marsh, Nelemans, and Steeghs (2004)



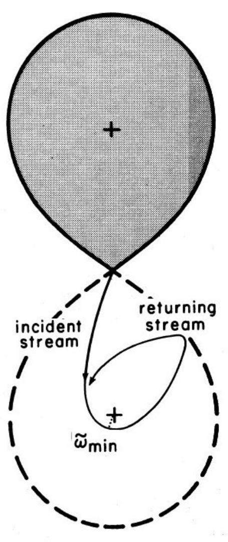
Outline

Angular Momentum and Mass Transfer

Lubow & Shu (1975), Verbunt & Rappaport (1988), Nelemans et al. (2001)

ΔJ due to Mass Transfer

- Mass, M_P, ejected from L_1 with some velocity $\vec{v}$, removing J from orbit
- Which changes over the path of the mass
- $\langle J_P \rangle \rightarrow \Delta J_{MT} \rightarrow \sqrt{G M_A R_h} M_P$
- Upon accretion: $\Delta J_{\mathrm{spin,A}} = J_P$

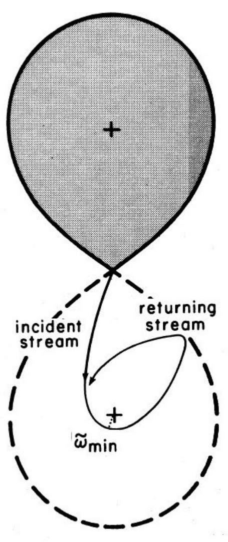


Angular Momentum and Mass Transfer

Lubow & Shu (1975), Verbunt & Rappaport (1988), Nelemans et al. (2001)

But...

- J_P is not constant
  J_P at impact is not equal to $\langle J_P \rangle$
- Angle of impact matters



Angular Momentum and Mass Transfer

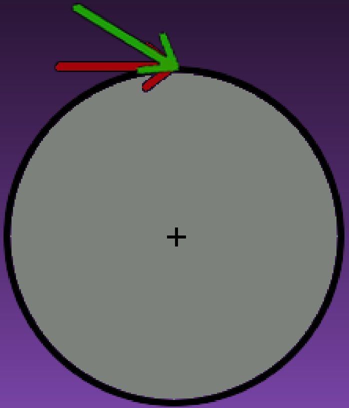
Lubow & Shu (1975), Verbunt & Rappaport (1988), Nelemans et al. (2001)

But...

- J_P is not constant
  J_P at impact is not equal to $\langle J_P \rangle$
- Angle of impact matters

Impact Angle

- Oblique impacts will change both the Spin *and* Orbital Angular Momentum of the accretor

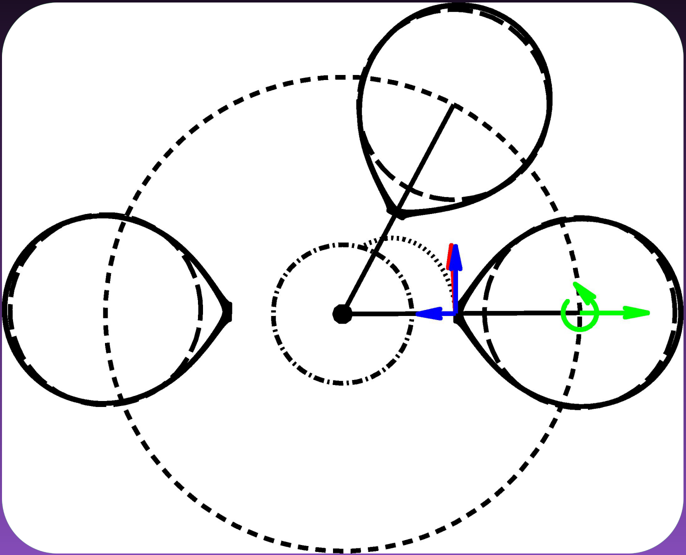


New (Basic?) Model

Our Method

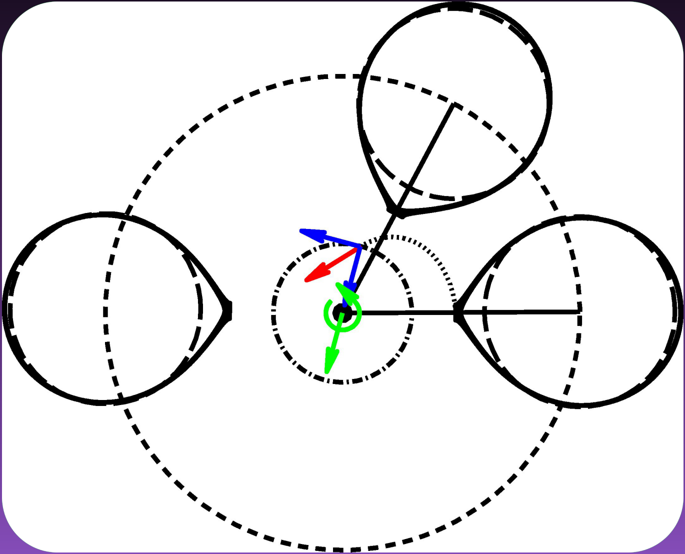
Rigid Spheres Conserving Both Linear and Angular Momentum

Sepinsky et al. (2010)



Our Method

Rigid Spheres Conserving Both Linear and Angular Momentum
Sepinsky et al. (2010)



What Changes After One Orbit?

Highlighted momenta changes are *not* included in the standard model

Angular Momenta

- **Donor Orbital Angular Momentum** $\rightarrow$ Changes in size/shape of orbit
- **Accretor Orbital Angular Momentum** $\rightarrow$ Changes in size/shape of orbit
- **Accretor Spin Angular Momentum** $\rightarrow$ Sink of Angular Momentum; Source of Tidal Angular Momentum
- **Donor Spin Angular Momentum** $\rightarrow$ Source of Angular Momentum; Sink of Tidal Angular Momentum

What Changes After One Orbit?

Highlighted momenta changes are *not* included in the standard model

Angular Momenta

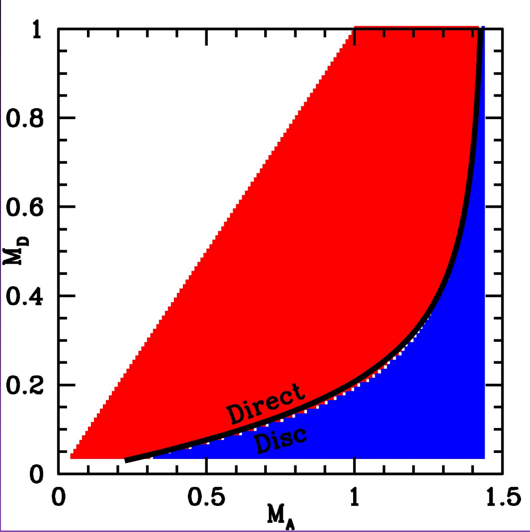
- **Donor Orbital Angular Momentum** → Changes in size/shape of orbit
- **Accretor Orbital Angular Momentum** → Changes in size/shape of orbit
- **Accretor Spin Angular Momentum** → Sink of Angular Momentum; Source of Tidal Angular Momentum
- **Donor Spin Angular Momentum** → Source of Angular Momentum; Sink of Tidal Angular Momentum

Angular Momentum Balance

$$\dot{J}_{\mathrm{orb}} = \dot{J}_{GW} + \dot{J}_{MT} + \dot{J}_{\mathrm{tides,A}} + \dot{J}_{tides,D}$$

Ballistic Numerical Integrations

Consistent with Lubow & Shu (1975)



Solid Line: where r_{min} from Lubow &Shu (1975) equals the Accretor Radius

Outline

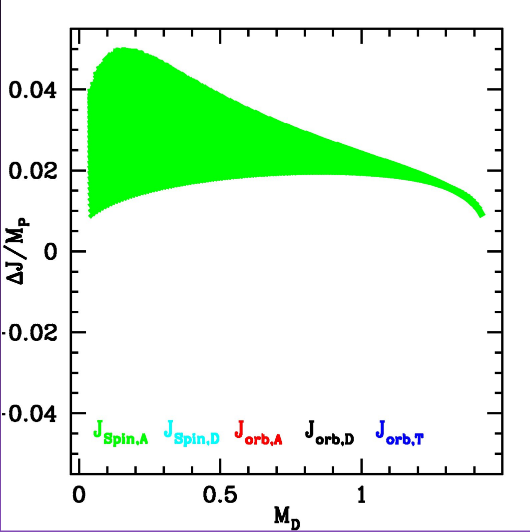
1. Motivation & Background
2. Ballistic Model Revisited
3. Results and Analysis
4. Conclusions & Future Work

Angular Momentum Changes

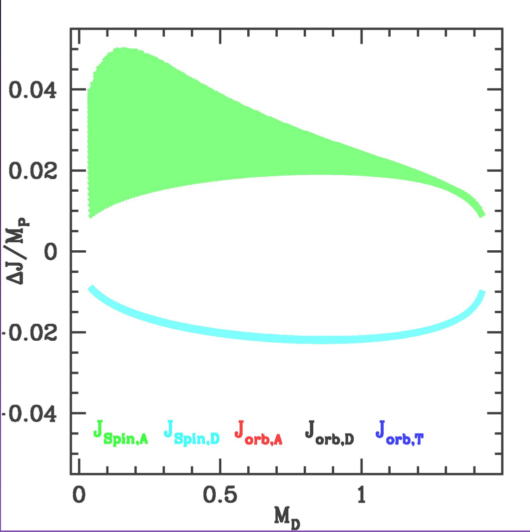
Calculations

- Eject a ballistic particle from the L_1 of the Donor WD, conserving Linear and Angular Momentum
- Numerically integrate the trajectory, conserving total momentum and energy
- For direct impact: Accrete the ballistic particle, conserving angular and linear momentum of the donor
- Calculate the total changes in the orbital and spin angular momentum of each component

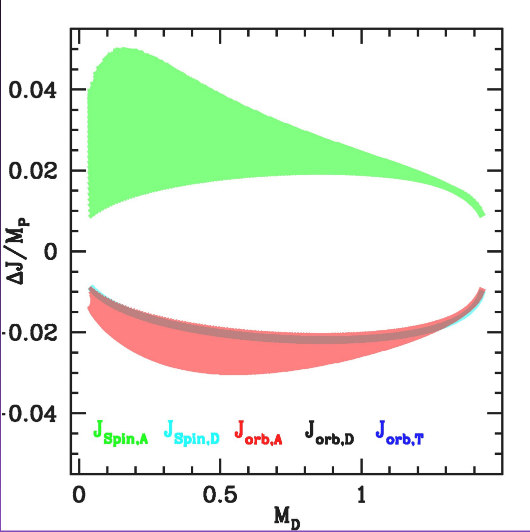
Angular Momentum Changes



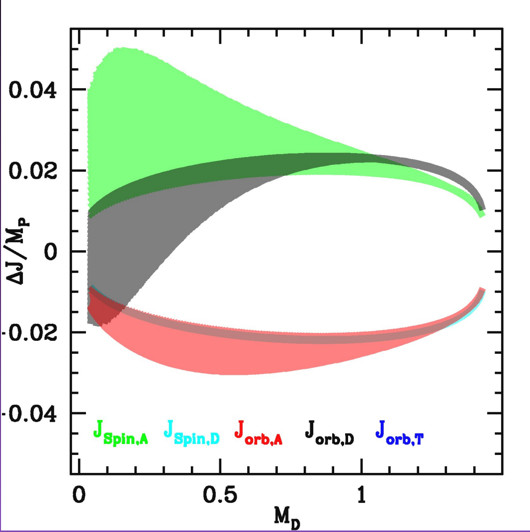
Angular Momentum Changes



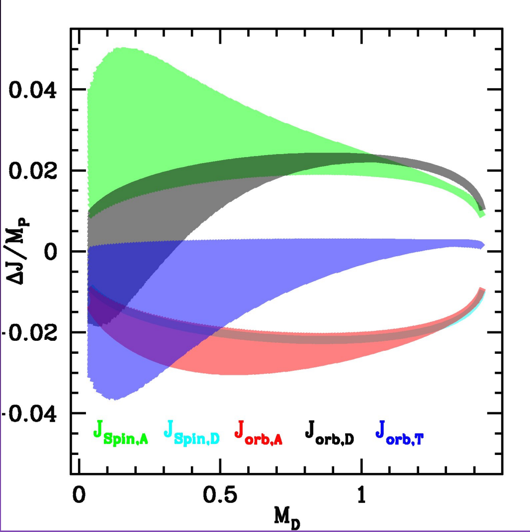
Angular Momentum Changes



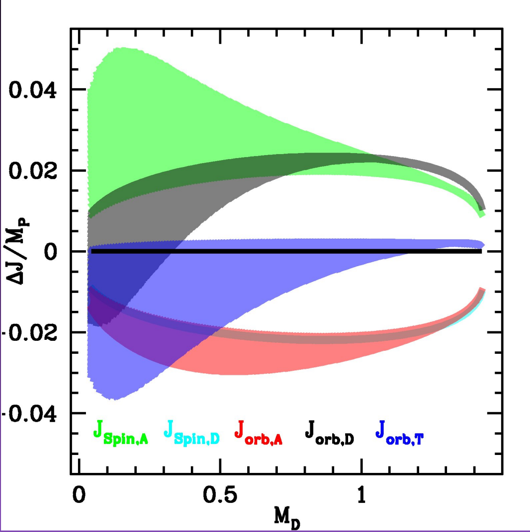
Angular Momentum Changes



Angular Momentum Changes

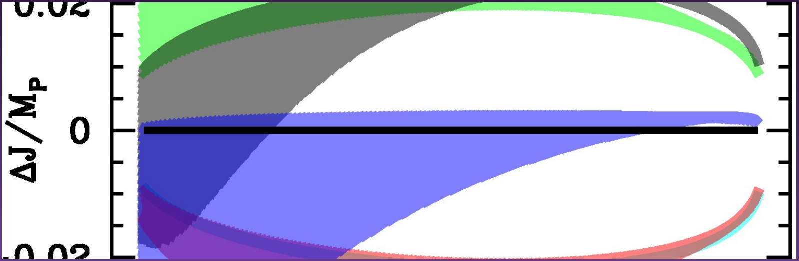


Angular Momentum Changes



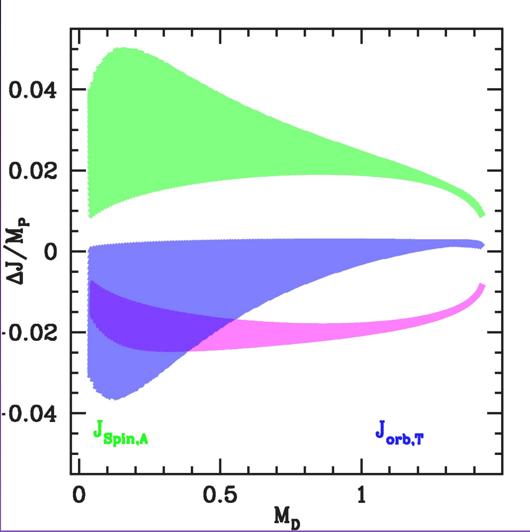
Angular Momentum Changes

The Orbital Angular Momentum can Increase!



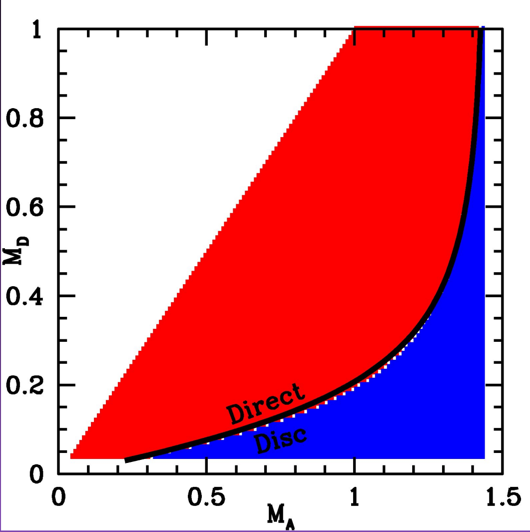
Comparison with Previous Work

Magenta: Average particle orbital angular momentum from Verbunt & Rappaort (1988)



Angular Momentum and Stability

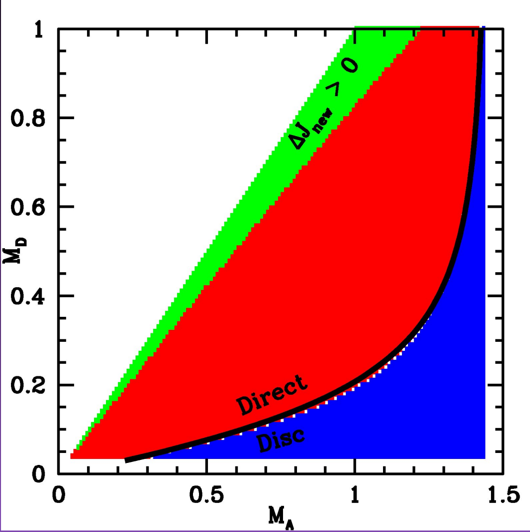
So what does all this mean?



Solid Line: where r_{min} from Lubow & Shu (1975) equals the Accretor Radius

Angular Momentum and Stability

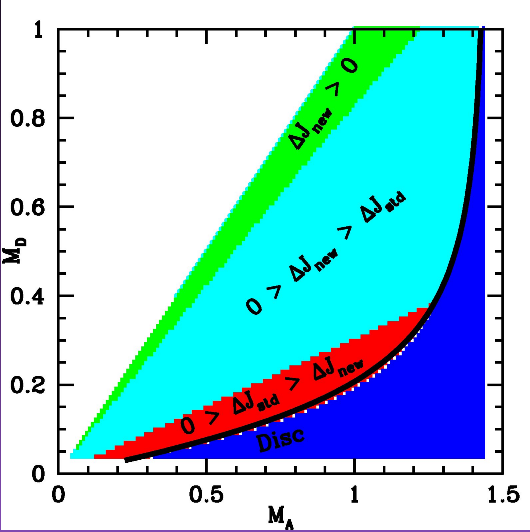
So what does all this mean?



Solid Line: where r_{min} from Lubow & Shu (1975) equals the Accretor Radius

Angular Momentum and Stability

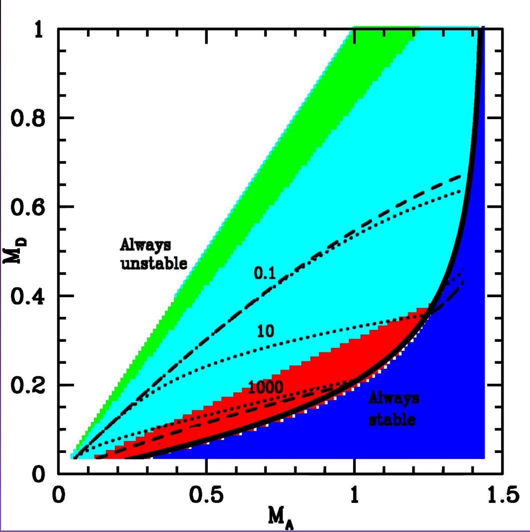
So what does all this mean?



Solid Line: where r_{min} from Lubow & Shu (1975) equals the Accretor Radius

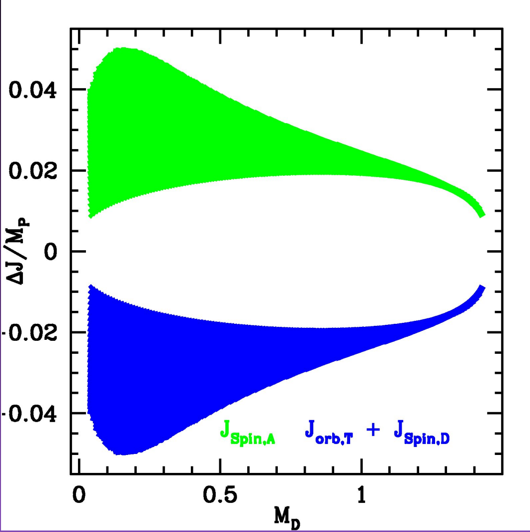
Angular Momentum and Stability

So what does all this mean?

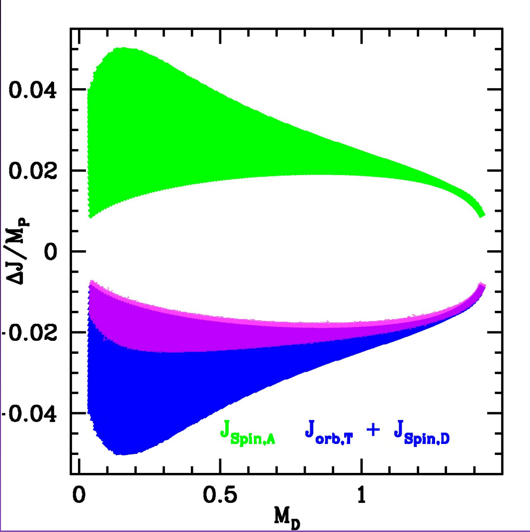


Solid Line: where r_{min} from Lubow & Shu (1975) equals the Accretor Radius

Assuming Donor Remains Synchronous



Assuming Donor Remains Synchronous



Outline

Conclusions & Future Work

Conclusions

- Conservation of angular momentum during ejection and accretion change the spin of each star, as well as their orbital angular momentum
- The resultant change in the total angular momentum can be significantly different than the standard model and may *increase* the orbital angular momentum of the system
- This may affect the stability of mass transfer and may significantly change the survivability of DWD into AM CVn

Conclusions & Future Work

Future Work

The new rates of change of orbital angular momentum bring up three important areas of future work

- How do the new momenta changes affect the instantaneous stability?
- What does the long term, steady-state system look like?
- What role does an asynchronous donor play in the evolution of the system?

Conclusions & Future Work

Future Work

The new rates of change of orbital angular momentum bring up three important areas of future work

- How do the new momenta changes affect the instantaneous stability?
- What does the long term, steady-state system look like?
- What role does an asynchronous donor play in the evolution of the system?

Thank you! Any Questions?

The Equations

On Ejection (For more details see Sepinsky et al. (2010)

Shift in the Center of mass:

$$\Delta \vec{R}_D = -\frac{M_P}{M_D - M_P}\left(\vec{R}_P - \vec{R}_D\right) \tag{1}$$

Shift in the Linear Momentum:

$$\Delta \vec{V}_D = -\frac{M_P}{M_D - M_P}\left(\vec{V}_P - \vec{V}_D\right) \tag{2}$$

Change in Spin Angular Momentum:

$$\Delta J_{\mathrm{Spin,D}} = -\frac{M_D M_P}{M_D - M_P}\left[\left(\vec{R}_P - \vec{R}_D\right) \times \left(\vec{V}_P - \vec{V}_D\right)\right] \tag{3}$$

The Equations

Then A Numerical Integration Occurs. . .

The Equations

On Accretion (For more details see Sepinsky et al. (2010)

Shift in the Center of mass:

$$\Delta \vec{R}_A = \frac{M_P}{M_A + M_P}\left(\vec{R}_P - \vec{R}_A\right) \quad (1)$$

Shift in the Linear Momentum:

$$\Delta \vec{V}_A = \frac{M_P}{M_A + M_P}\left(\vec{V}_P - \vec{V}_A\right) \quad (2)$$

Change in Spin Angular Momentum:

$$\Delta J_{\rm Spin,A} = \frac{M_A M_P}{M_A + M_P}\left[\left(\vec{R}_P - \vec{R}_A\right) \times \left(\vec{V}_P - \vec{V}_A\right)\right] \quad (3)$$