Mass Loss in Rotating Stellar Models

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November 5, 2010

Stellar Winds

- Massive stars lose mass through radiative line driving
- Provides energy and momentum to the ISM
- Can produce circumstellar shells - expected to affect subsequent supernovae
- Mass loss influences the stellar evolution
- Affects atmospheric structure - needs to be understood to derive stellar paremeters

Stellar Winds

Credit: NASA, ESA, Y. Nazé and Y.-H. Chu

Theory - CAK

Original theory describing radiatively driven winds derived by Castor, Abbott and Klein (1979)
made 4 basic assumptions:

- The Sobolev approximation

Radiative interactions are determined locally

Theory - CAK

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- Core-halo separation

Assume the continuum, which is formed in the photosphere is formed at a different level than lines
Can then take the continuum intensity to be constant in the wind

Theory - CAK

Original theory describing radiatively driven winds derived by Castor, Abbott and Klein (1979)
made 4 basic assumptions:

- The Sobolev approximation
- Core-halo separation
- No limb-darkening

Intensity (and flux) are the same across the visible disk

Theory - CAK

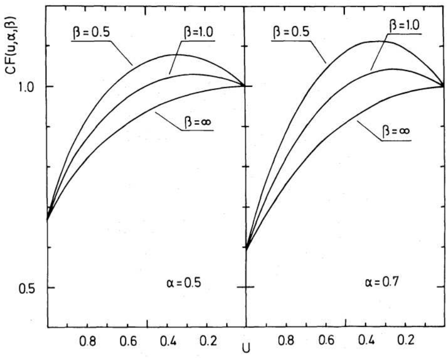
Original theory describing radiatively driven winds derived by Castor, Abbott and Klein (1979)
made 4 basic assumptions:

- The Sobolev approximation
- Core-halo separation
- No limb-darkening
- Radial streaming

All photons travel only radially - no angular contribution
This is expected to hold far from the star, but is not a good approximation close to the surface

Theory - Kudritzki et al

- Extension to CAK theory - relaxes 4^{th} assumption
- Photons now have an angular component
- Analytic solutions worked out by Kudritzki et al, 1989



Kudrtizki et al, 1989

Mass loss Rates

Compare 3 mass loss rate prescriptions:

- Castor, Abbott & Klein (1979) (CAK)

The original theoretical derivation of mass loss rates

$$\dot{M} \propto L$$

Dependence on metallicity is not explicit

Mass loss Rates

Compare 3 mass loss rate prescriptions:

- Castor, Abbott & Klein (1979) (CAK)
- Kudritzki et al (1989)

Basically the same as CAK, but includes the finite disk effects

Mass loss Rates

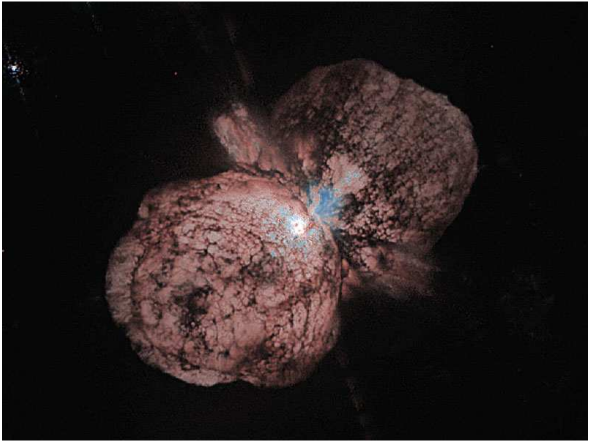
Compare 3 mass loss rate prescriptions:

- Castor, Abbott & Klein (1979) (CAK)
- Kudritzki et al (1989)
- Vink, de Koter & Lamers (2001)

Based on Monte Carlo calculations of radiation transfer in stellar atmosphere models

$$\dot{M} \propto L, M, T_{eff} \text{ and } Z$$

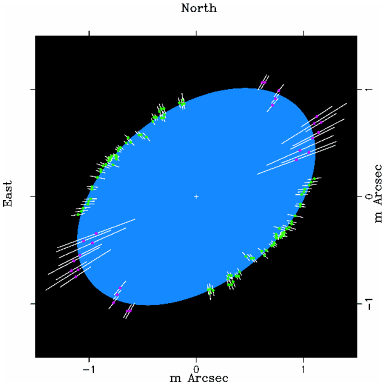
Rotation



Credit: J. Morse, K. Davidson et al., WFPC2, HST, NASA

Rotation

- Many massive stars are known to rotate - probably most are born as rapid rotators
- Rotation causes the star to become flattened
- Pole becomes hotter than equator (eg., von Zeipel, 1924)



Domiciano de Souza et al, 2003

Stellar Models

- 2D stellar structure and evolution code, ROTORC (Deupree 1990, 1995)
- Use fractional radius, $x = r/R_{eq}$ and θ as independent variables
- Surface defined to be an equipotential
- flux, temperature and radius all allowed to vary as a function of θ

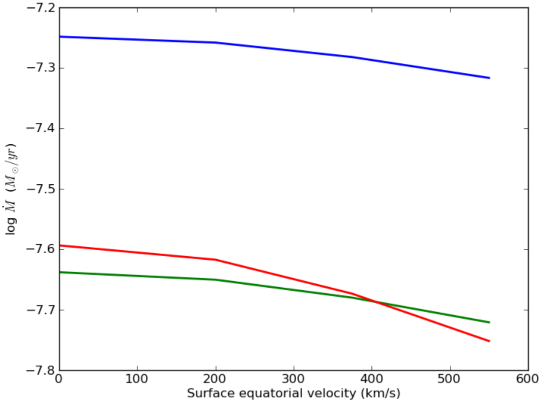
Stellar Models

20 $M_\odot$ ZAMS models:

V_{eq} (km/s)	Ω/Ω_c	R_{eq} ($R_\odot$	R_p/R_{eq}	T_{eff} (K)	ΔT (K)	$L/L_\odot$
0	0	5.835	1.000	34476	0	42899
200	0.3	5.991	0.969	34090	1161	42313
375	0.5	6.437	0.892	33168	3866	41196
550	0.7	7.376	0.770	31802	7899	40122

1D Models

blue - CAK
red - Kudritzki
green - Vink



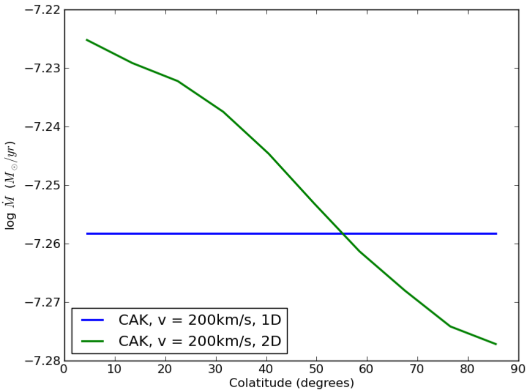
Mass loss in 2D

- Δ T_{eff} in these models ranges from 1200K at 200 km/s to almost 8000K at 550 km/s
- Mass loss rates are sensitive functions of effective temperature

Mass loss in 2D

- Δ T_{eff} in these models ranges from 1200K at 200 km/s to almost 8000K at 550 km/s
- Mass loss rates are sensitive functions of effective temperature
- How will this change the mass loss rates?

2D Models

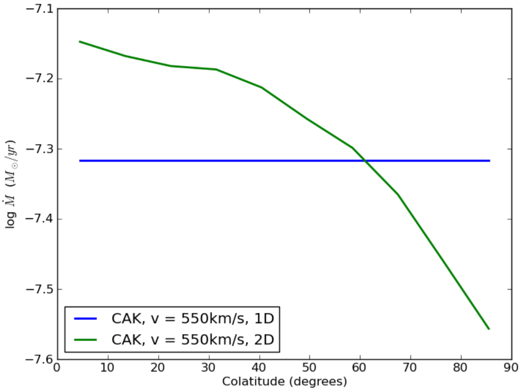


$$200 \text{ km/s} = 0.3\ \Omega_c$$

2D Models

- 2D mass loss rate is 0.03 dex larger at the pole, 0.02 dex smaller at the equator
- Total mass lost is the same to within about 0.1 %
- But: mass loss is 8 % greater at pole, 4 % lower at the equator

2D Models

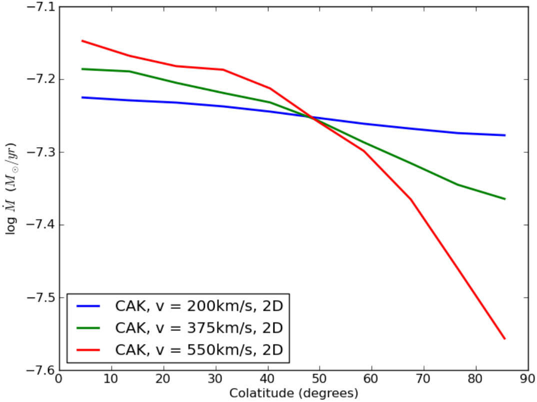


$$550 \text{ km/s} = 0.7\ \Omega_c$$

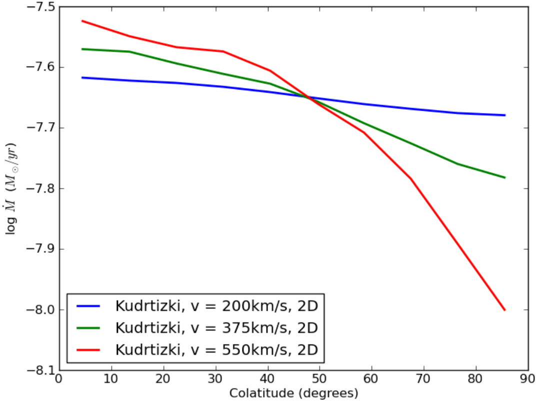
2D Models

- 2D mass loss rate is now 0.15 dex larger at the pole, 0.2 dex smaller at the equator
- Difference in total mass lost is still less than 1 %
- But: mass loss is 47 % greater at pole, 42 % lower at the equator

2D Models

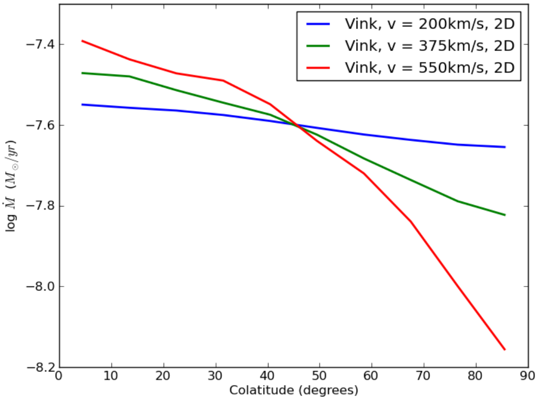

−7.1
−7.2
−7.3
−7.4
−7.5
−7.6
log $\dot{M}$ $(M_\odot/yr)$
0
10
20
30
40
50
60
70
80
90
Colatitude (degrees)
CAK, v = 200km/s, 2D
CAK, v = 375km/s, 2D
CAK, v = 550km/s, 2D

2D Models



−7.5
−7.6
−7.7
−7.8
−7.9
−8.0
−8.1
0
10
20
30
40
50
60
70
80
90
log $\dot{M}$ $(M_\odot/yr)$
Colatitude (degrees)
Kudrtizki, v = 200km/s, 2D
Kudrtizki, v = 375km/s, 2D
Kudrtizki, v = 550km/s, 2D

2D Models


Vink, v = 200km/s, 2D
Vink, v = 375km/s, 2D
Vink, v = 550km/s, 2D
−7.4
−7.6
−7.8
−8.0
−8.2
0
10
20
30
40
50
60
70
80
90
Colatitude (degrees)
log $\dot{M}$ $(M_\odot/yr)$

2D Corrections to 1D Models

Calculate effects of rotation in 1D:
Effects of gravity are reduced by a centrifugal term:

$$g_{eff} = \frac{GM}{R^2}\left(1 - \frac{V_{rot}^2 R}{GM} sin^2\theta\right)$$

then:

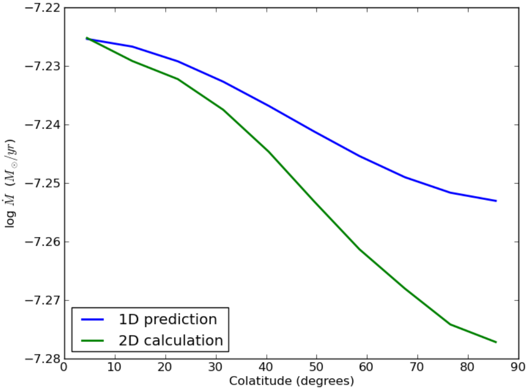
$$\frac{\dot{m}(\theta)}{\dot{m}_o} = \left[\frac{F(\theta)}{F_o}\right]^{1/\alpha}\left[\frac{g_{eff}(\theta)}{g_o}\right]^{1-1/\alpha}$$

2D Corrections to 1D Models

Assume von Zeipel's law holds: $F(\theta) \sim g_{eff}(\theta)$
then:

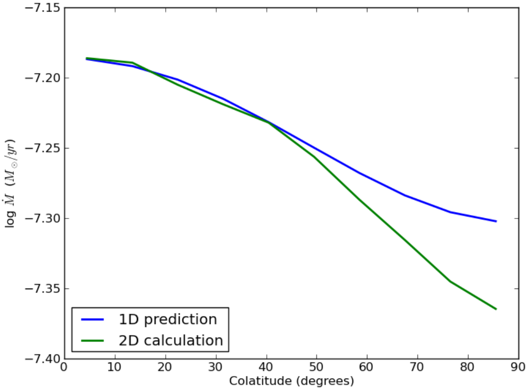
$$\frac{\dot{m}(\theta)}{\dot{m}_o} = 1 - \frac{V_{rot}^2 R}{GM} sin^2\theta$$

Comparing 2D Corrections to 2D Models



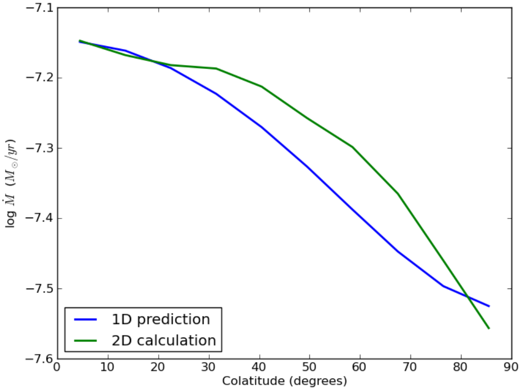
$\Delta_{eq} = 0.024$

Comparing 2D Corrections to 2D Models



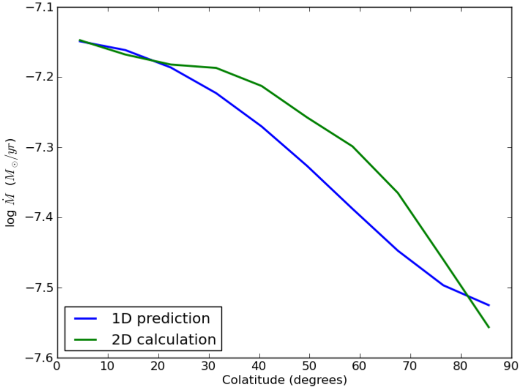
$\Delta_{eq} = 0.062$

Comparing 2D Corrections to 2D Models



$\Delta_{eq} = 0.03$

Comparing 2D Corrections to 2D Models



$\Delta_{40^\circ} = 0.06$

Conclusions

- Vink mass loss rates agree with theoretical predictions from Kudritzki
- Even at low rotation rates (0.3 Ω_c) 2D effects can be important
- Rotation effects become more pronounced as rotation rate increases
- Simple 1D calculations underestimate mass loss at pole, overestimate loss at equator
- 2D corrections to 1D rates using von Zeipel's law are better, but still overestimate mass loss at equator
- Change in distribution of mass loss will change amount of angular momentum lost

Future Work

- Calculate angular momentum loss from 2D models
- Incorporate mass loss into evolution models
- Study how accumulated differences affect evolution
- Models can be used as input for other problems - supernovae, X-ray binaries, etc