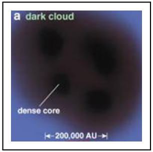
Disks in Astrophysics

Brian Kloppenborg
University of Denver

August 6, 2009

Outline

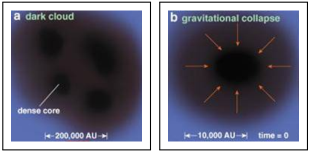
Single Star Formation



Images Courtsey of SSC IR Compendium

a Cloud of gas and dust

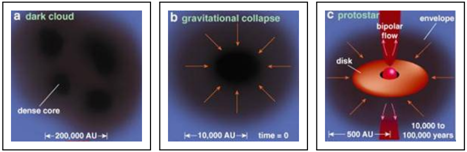
Single Star Formation



Images Courtsey of SSC IR Compendium

- a Cloud of gas and dust
- b Gravitational collapse

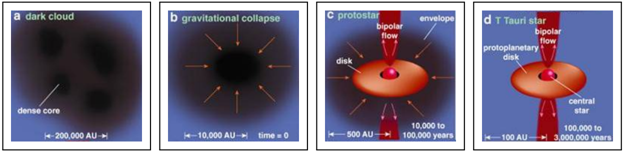
Single Star Formation



Images Courtsey of SSC IR Compendium

- a Cloud of gas and dust
- b Gravitational collapse
- c Conservation of angular momentum and collisions cause disk to form.

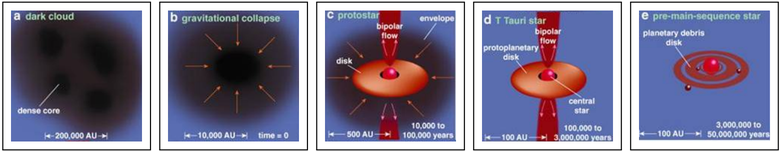
Single Star Formation



Images Courtsey of SSC IR Compendium

a Cloud of gas and dust
b Gravitational collapse
c Conservation of angular momentum and collisions cause disk to form.
d Envelope has dissapated or collapsed into the disk.

Single Star Formation



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a Cloud of gas and dust

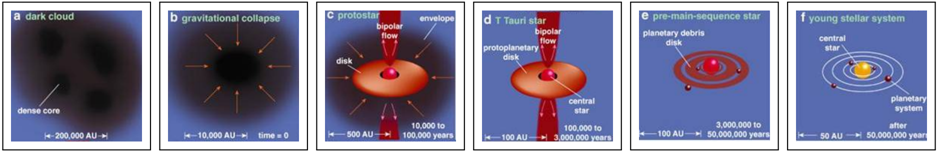
b Gravitational collapse

c Conservation of angular momentum and collisions cause disk to form.

d Envelope has dissapated or collapsed into the disk.

e Collisions inside disk cause planetesimals for form, clearing the disk of debris.

Single Star Formation



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a Cloud of gas and dust

b Gravitational collapse

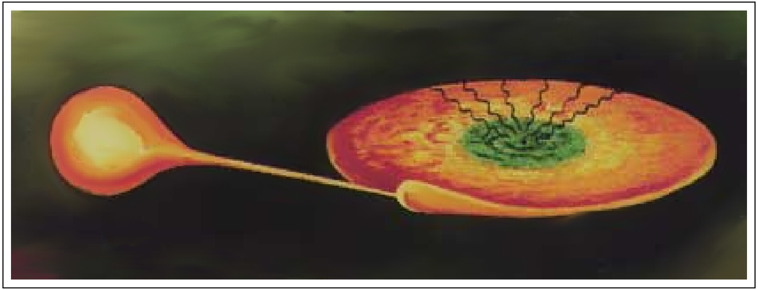
c Conservation of angular momentum and collisions cause disk to form.

d Envelope has dissapated or collapsed into the disk.

e Collisions inside disk cause planetesimals for form, clearing the disk of debris.

f Star "ignites" hydrogen in its core.

Binary Star Evolution



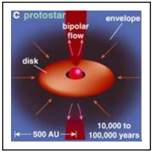
Artist's impression of 4U 1820-30, image courtsey of NASA's HEASARC

Like single star evolution except:

- Roche Lobe Overflowing
- Mass Transfer Streams
- Ensuing Disk Hot Spots

Disk Evolution

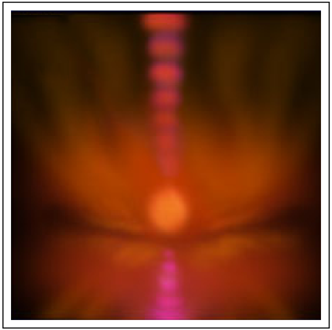
Artist Impressions of Disk Evolution



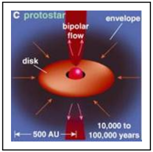
Disk Evolution

Artist Impressions of Disk Evolution

Slightly Above Disk



Images Courtesy of STScI

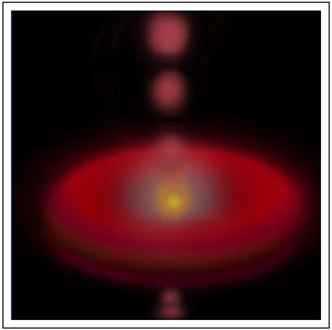


Edge-On

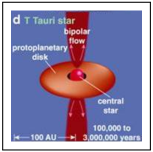
Disk Evolution

Artist Impressions of Disk Evolution

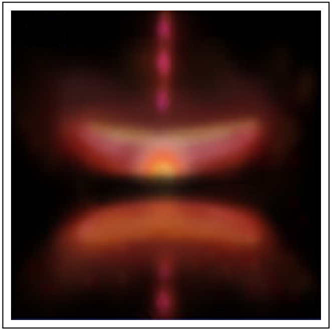
Slightly Above Disk



Images Courtesy of STScI



Edge-On



Disk Evolution

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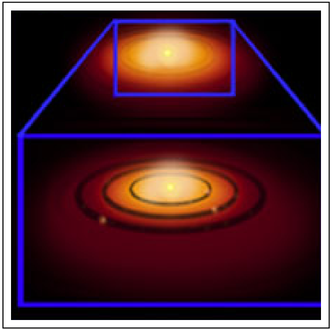
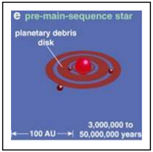


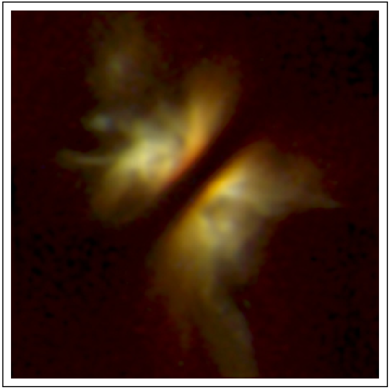


Edge-On

Images Courtesy of STScI

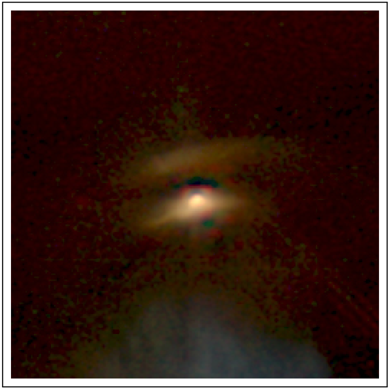
Direct Imaging

Butterfly Star



Karl Stapelfeldt (JPL) and colleagues, and NASA

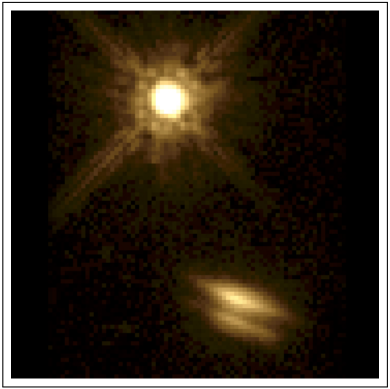
Herbig-Haro (HH) 6-5



D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA

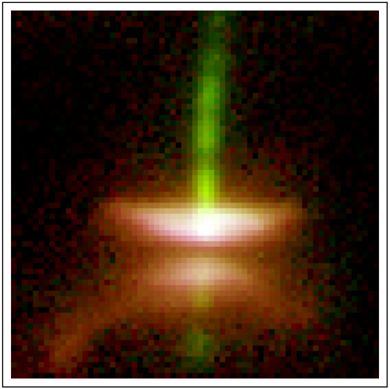
Direct Imaging

HK Tauri



Karl Stapelfeldt (JPL) and colleagues, and NASA

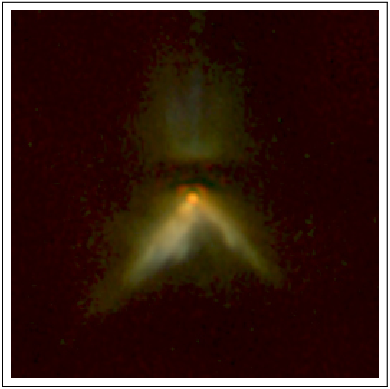
HH 30



Chris Burrows (STScI), the WFPC2 Science Team and NASA

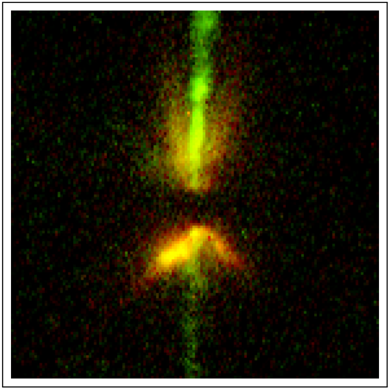
Direct Imaging

DG Tauri B



(IR), D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA

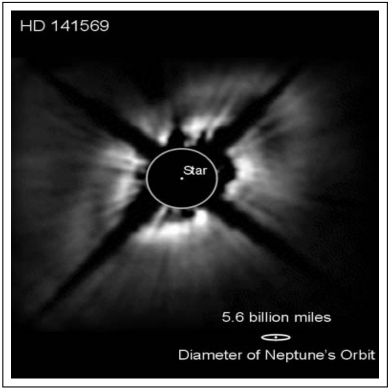
DG Tauri B



(Hubble), Chris Burrows (STScI), the WFPC2 Science Team and NASA

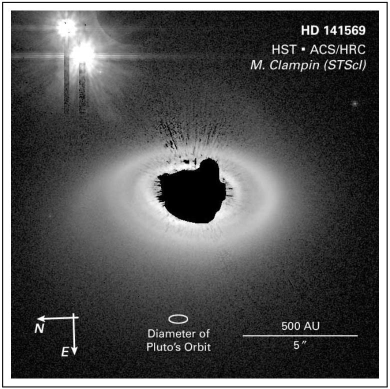
Direct Imaging

HD 141569



(Near IR), B. Smith (U. Hawaii), A. Weinberger, E. Becklin (UCLA), and G. Schneider (U. Arizona)

HD 141569



(Hubble), M. Clampin (NASA Goddard)

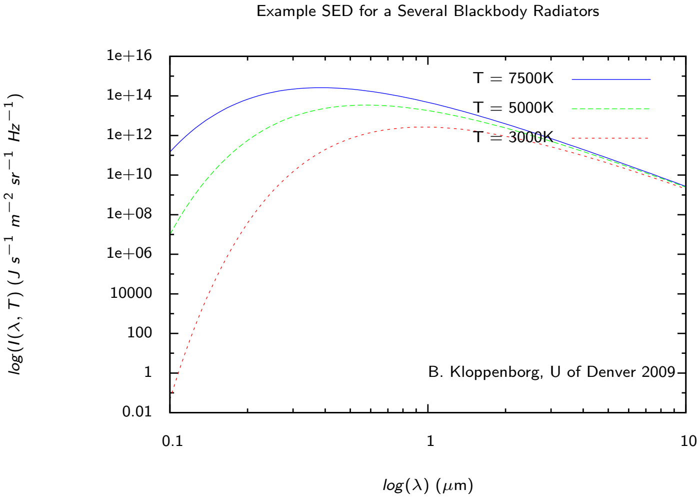
Spectral Energy Distributions (SEDs)

Spectral Energy Distributions (SEDs)

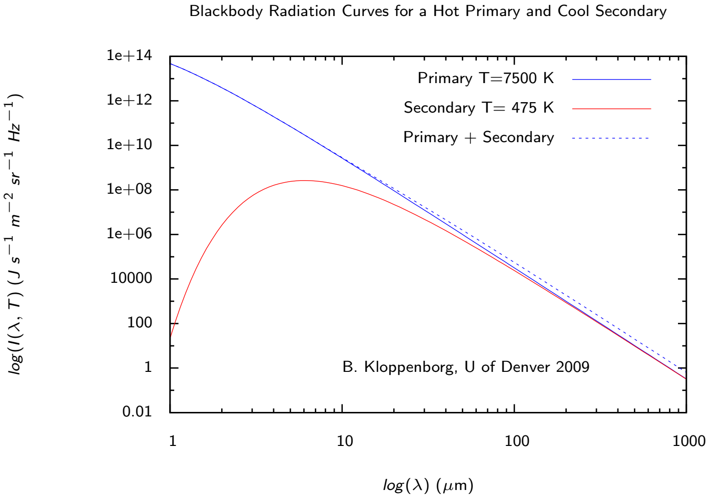
Blackbody Radiation is a First-Order approximation for radiation from objects. Blackbody radiation is described by Planck's Law:

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k T}} - 1}$$

Spectral Energy Distributions (SEDs)



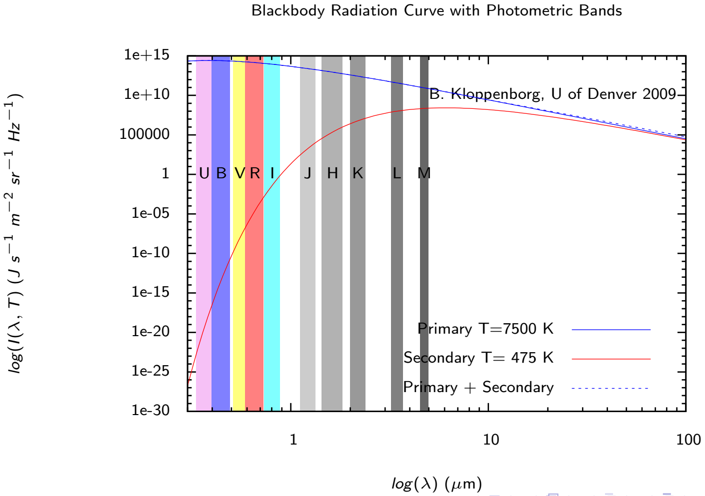
Spectral Energy Distributions (SEDs)



Photometry

Photometry measures the brightness of stars in specific passbands.

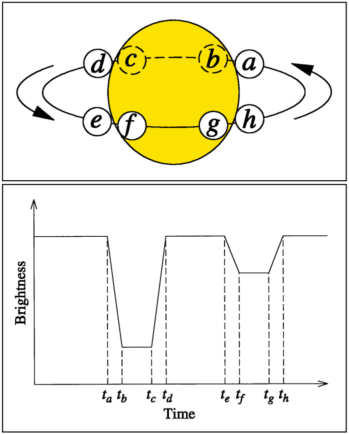
Photometry


Blackbody Radiation Curve with Photometric Bands
1e+15
1e+10
100000
1
1e-05
1e-10
1e-15
1e-20
1e-25
1e-30
U B V R I J H K L M
B. Kloppenborg, U of Denver 2009
Primary T=7500 K
Secondary T= 475 K
Primary + Secondary
1
10
100
$log(I(\lambda, T))$ $(J\ s^{-1}\ m^{-2}\ sr^{-1}\ Hz^{-1})$
$log(\lambda)$ (μm)

Photometry

Photometry Can Determine

- Period of variable stars, minor planets, AGNs, transiting extrasolar planets.



Eclipsing Binary With Light Curve (Ostlie 1996)

Photometry

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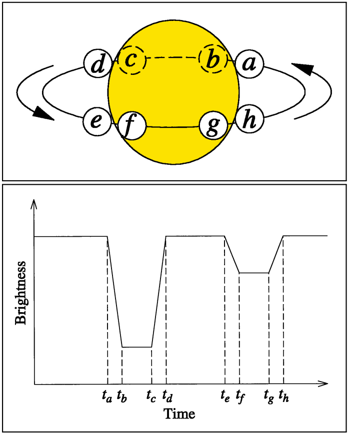
- Luminosity of an object (if distance is known).



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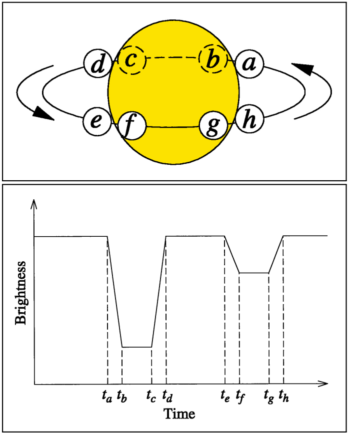

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Photometry

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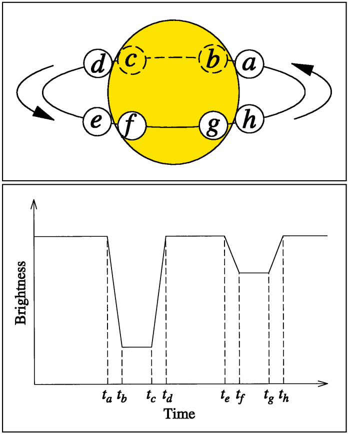
- Period of variable stars, minor planets, AGNs, transiting extrasolar planets.
- Luminosity of an object (if distance is known).
- Blackbody Temperature of an object.
- Total energy output of supernovae.

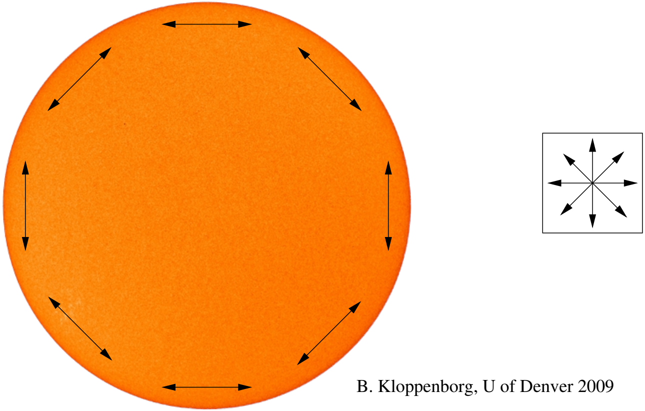


Eclipsing Binary With Light Curve (Ostlie 1996)

Polarimetry

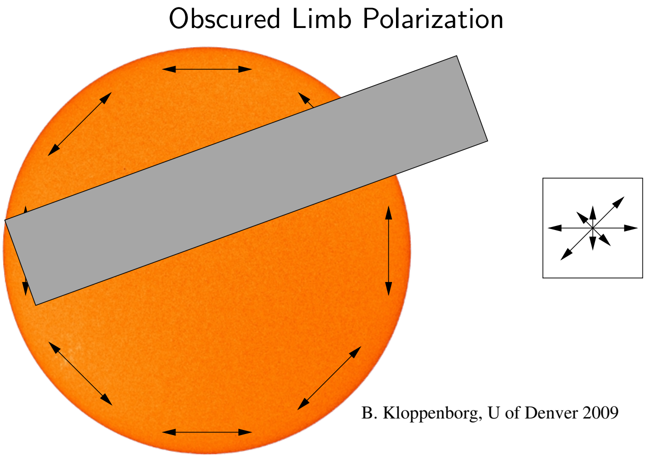
Polarimetry

Limb Polarization



Limb Polarization.
MDI Continuum image of the Sun courtesy of SOHO

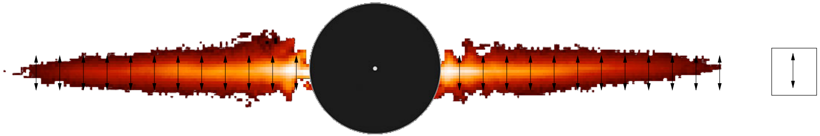
Polarimetry



Obscured Limb Polarization.
MDI Continuum image of the Sun courtesy of SOHO

Polarimetry

A Disk Can Cause a Net Polarization.



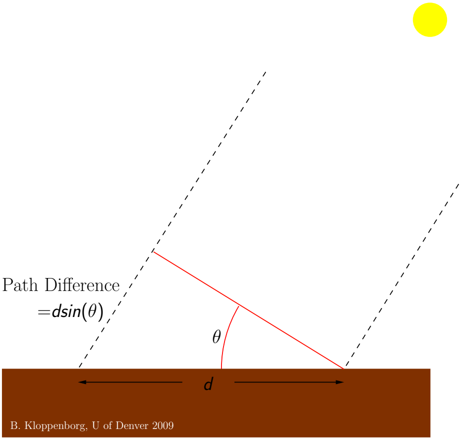
Polarization from a Disk.
HST Image of AU Mic Debris Disk courtesy of NASA, ESA, and J. Graham (UC, Berkeley)

Interferometry

Interferometry provides a method of indirectly imaging objects too small for traditional imaging devices.

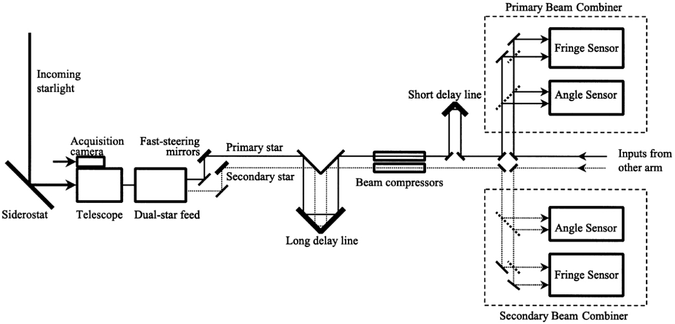
Interferometry

Interferometer Diagram



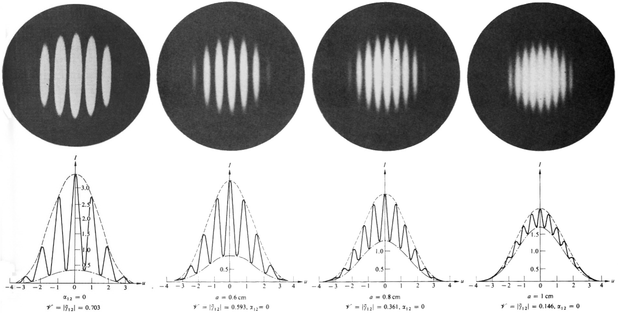
Interferometry

PTI Schematic Diagram



Schematic Drawing of PTI Optical Components (Colavita, 1999)

Fringes

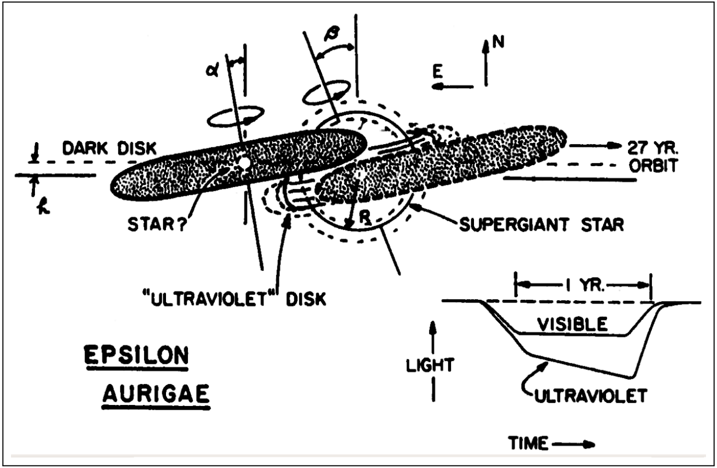


Fringes as seen by an Interferometer (Hecht, 2002)

Visibility Squared:

$$V^2 = \left(\frac{I_{max} - I_{min}}{I_{max} + I_{min}}\right)^2$$

Current Model of ϵ Aurigae



Model of ϵ Aurigae System (NASA, 1985)

Photometric Observations

Photometric Observations during Eclipse

1848 Schmidt (see Gussow, 1936), others?

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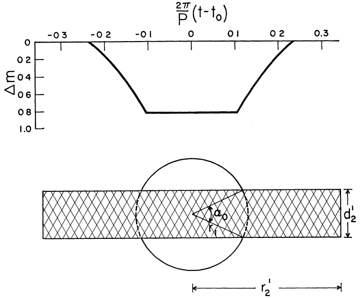
2009 *Your Name Here*

Models from Photometric Data

1965 Huang: Dark rectangular object moving across star face.

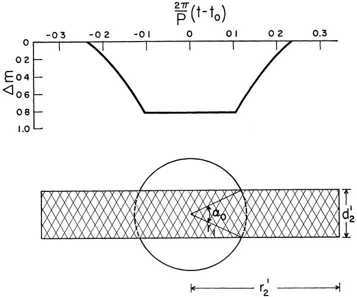


Schematic Diagram for ϵ Aur with light curve (Huang, 1965)

Models from Photometric Data

1965 Huang: Dark rectangular object moving across star face.

1971 Wilson: Geometrically Thin, Optically Thick disk with Hole in Center.



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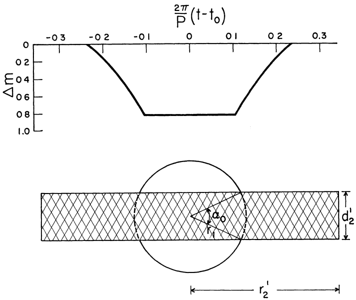
1974 Huang: Comparison of Thin/Thick Disk Models with Observed Light Curves.



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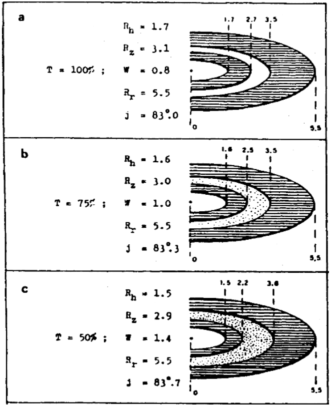
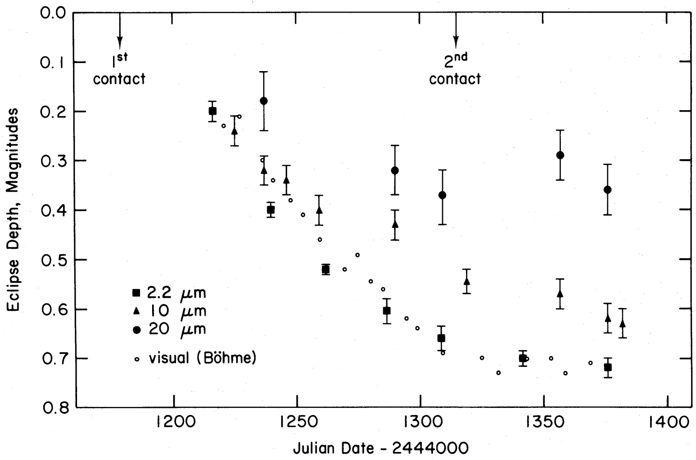
1990 Ferluga: Disk with Semitransparent Rings.



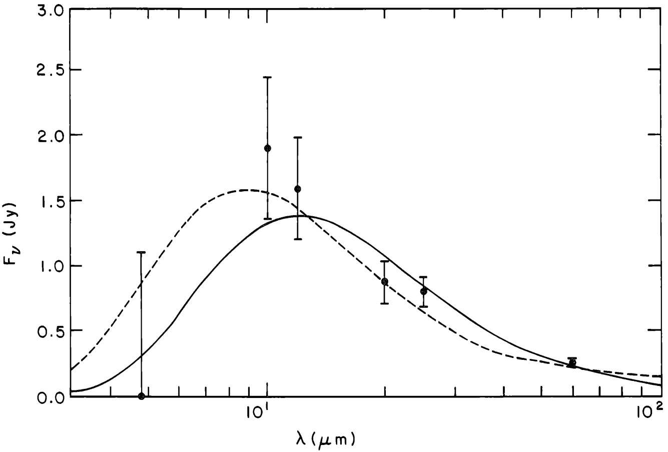
Three best-fitting ringed disk models to photometric curves. Units are in AU, j is the inclination angle (exaggerated in figures) (Ferluga, 1990)

Photometry



IR Excess as reported by Backman (1984)

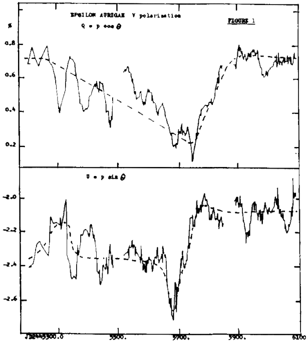
SEDs



IR Exceecss as found by IRAS (Backman, 1985). *Solid Line* opaque secondary, $T = 475\text{K}$, $\Omega = 8.6 \times 10^{-16}$ sr; *Dashed Line* optically thin secondary $T = 575\text{K}$, $\Omega = 4.4 \times 10^{-16}$ sr, particle radius 5.1 μm

Polarimetry

1985 Kemp: Polarization Curve During Eclipse with preliminary model.

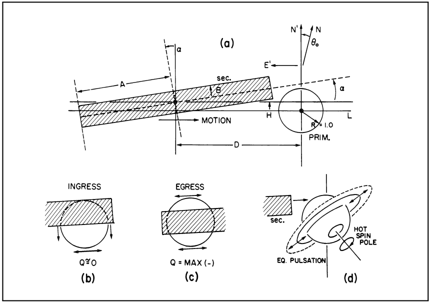


In-eclipse Polarization Data for ϵ Aur with light curve (Kemp, 1986)

Polarimetry

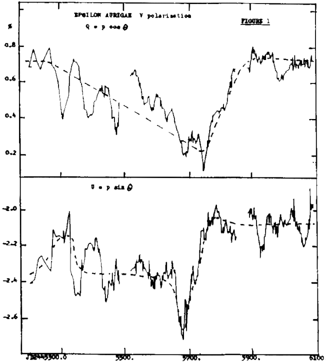
1985 Kemp: Polarization Curve During Eclipse with preliminary model.

1986 Kemp: Detailed Model for Polarization Curve.



Model for Polarization Data (Kemp, 1986)

Polarimetry



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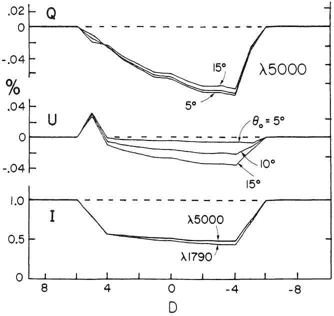
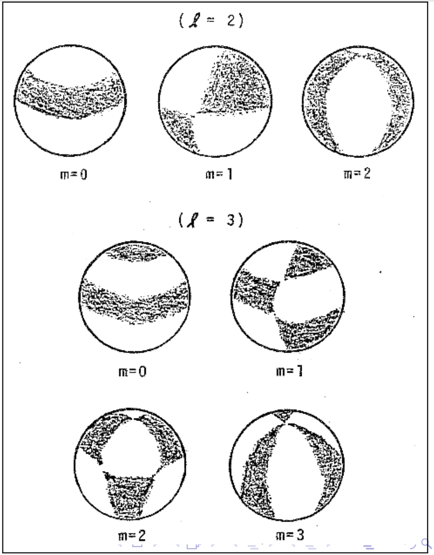


Theoretical Curves for Kemp's Model. (Kemp, 1986)

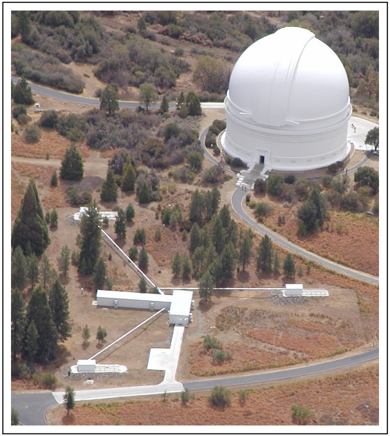
Polarimetry

- 1985 Kemp: Polarization Curve During Eclipse with preliminary model.
- 1986 Kemp: Detailed Model for Polarization Curve.
- 1989 Henson: Possible detection of non-radial pulsation.



Right: Possible Pulsation Modes of ϵ Aur (Henson, 1989)

Palomar Testbed Interferometer



Aerial View of PTI and the 200" Palomar Telescope (Gerald van Belle)

- PTI Operated by the Michelson Science Center on behalf of CalTech and NASA-JPL
- Maximum Baseline, 110 meters
- Resolution 1.67 - 2.18 mas (8.1 - 10.5 nano-radians)

PTI: Reduced Data

UTDate, JD-2,450,000	GMT start	Baseline*	Nscans	Mode	V^2	UDD [mas]	Error [mas]	V [mag]
2007Oct19, 4393	09:57	NS	14	K-low	0.516	2.19	0.06	3.036
2007Oct20, 4394	10:21	NS	6	K-high	0.544	2.16	0.12	3.036
2007Oct21, 4395	10:45	NS	3	K-low	0.583	1.90	0.13	3.036
2007Dec23, 4458	04:41	NW	6	K-low	0.574	2.36	0.14	3.046
2007Dec24, 4459	04:48	NW	6	K-low	0.565	2.37	0.11	3.043
2008Feb16, 4513	03:05	NW	2	K-low	0.527	2.60	0.15	2.98
2008Feb17, 4514	04:48	NW	5	K-low	0.572	2.28	0.15	2.98
2008Feb18, 4515	03:01	NW	5	K-low	0.624	2.25	0.12	2.98
New Data								
2008Oct26, 4765	08:20	NW	4	K-low	0.609	2.35	0.16	3.052
2008Oct26, 4765	08:30	NS	5	K-low	0.491	2.16	0.08	3.052
2008Nov8, 4778	08:49	NS	12	K-low	0.435	2.34	0.08	3.057
2009Nov9, 4779	09:22	NW	1	K-low	0.462	2.86	0.10	3.054
Archival Data								
1997Oct22, 0744	11:54	NS	1	K-low	0.376	2.50	0.17	2.986
1997Nov09, 0762	09:38	NS	2	K-low	0.438	2.32	0.09	2.977
1998Nov07, 1125	10:25	NS	4	K-low	0.515	2.09	0.10	2.997
1998Nov25, 1143	10:19	NS	2	K-low	0.458	2.25	0.08	2.998
2005Dec11, 3715	06:33	NW	86	Insufficient Data Points				3.02
2006Jan31, 3766	04:27	NW	86	No Cal Stars				3.08

Diameters obtained from Wide-Band Visibility mode data. *N-S baseline, 109 meters; N-W baseline, 86 meters.

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