



AGA0293 Astrofísica Estelar

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Capítulo 7

Estrelas Binárias e Parâmetros Estelares

7.1 Classificação de estrelas binárias

7.2 Determinação de Massas usando binárias visuais

7.3 Binárias Espectroscópicas Eclipsantes

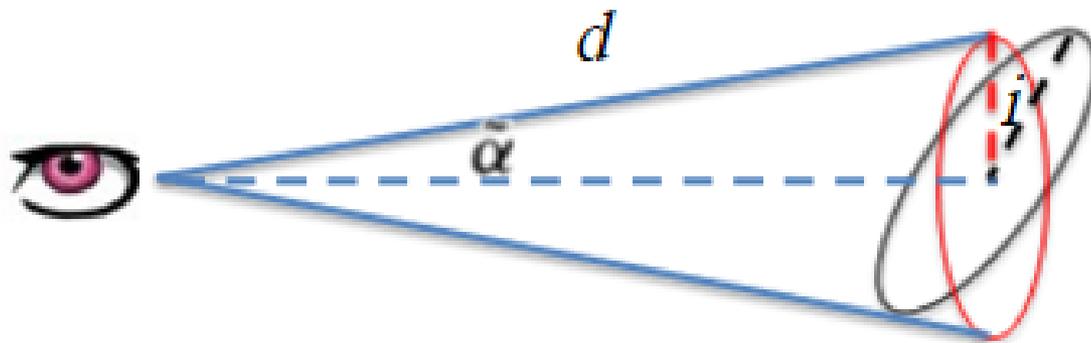
7.4 Detecção de exoplanetas

7.3 Binárias espectroscópicas eclipsantes

Outros **parâmetros estelares**, como **raio** e razão de T_{ef} (pela razão de fluxos), podem ser determinados das linhas espectrais duplas observadas em binárias.

Nos casos de componentes não resolvidas \rightarrow método usual não permite determinar orientação ou excentricidade do sistema.

Ângulo de inclinação também afeta determinação da massa \rightarrow influencia a medida da velocidade radial.



7.3 Binárias espectroscópicas eclipsantes

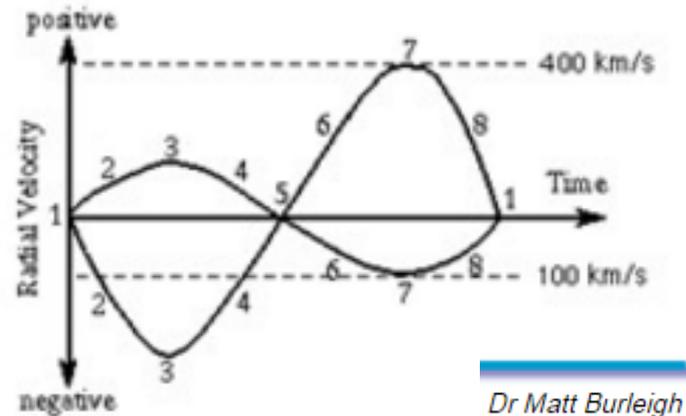
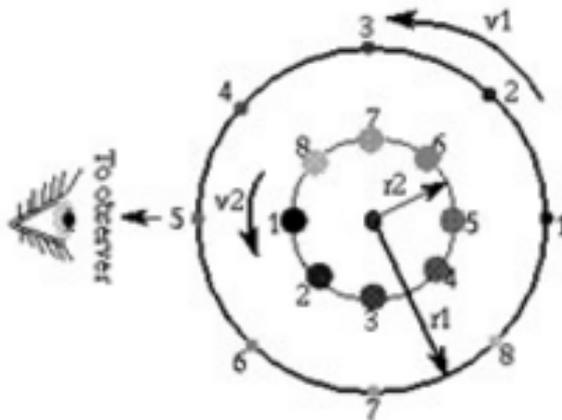
Efeito da Excentricidade na medida da velocidade radial

Considere a estrela 1 de massa m_1 e velocidade orbital v_1 num dado instante, e estrela 2 (m_2, v_2) \rightarrow a velocidade radial será

$$v_{1r} = v_1 \text{sen } i$$

$$v_{2r} = v_2 \text{sen } i$$

The simplest radial velocity curves are from those systems viewed edge-on ($i=90$ degrees). They appear sinusoidal with opposite phases e.g.



$$v_{1r} = v_1 \sin i$$

$$v_{2r} = v_2 \sin i$$

A velocidade radial depende da posição da estrela naquele instante. Se o movimento for perpendicular à linha de visada: $v_r=0$
 Se o plano da órbita está na linha de visada ($i=90^\circ$) temos uma variação senoidal

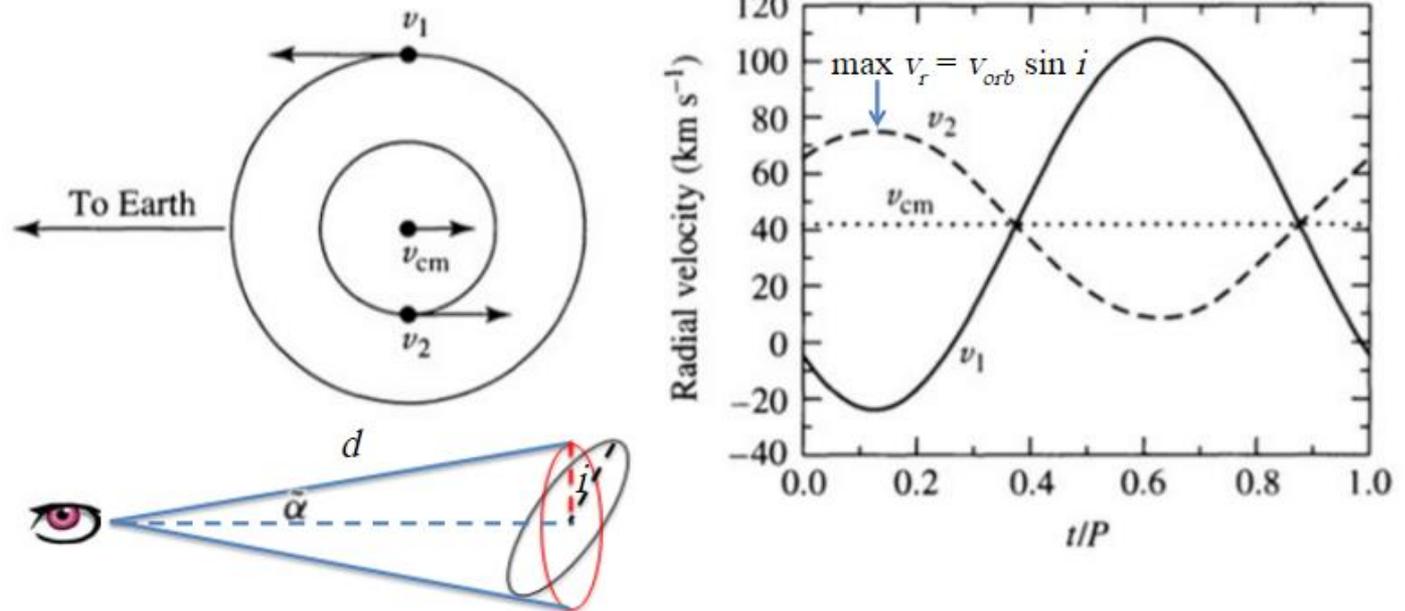
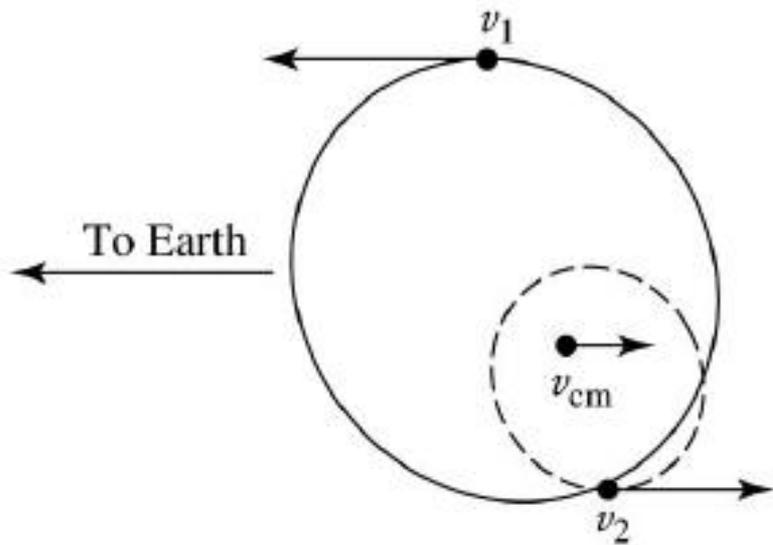
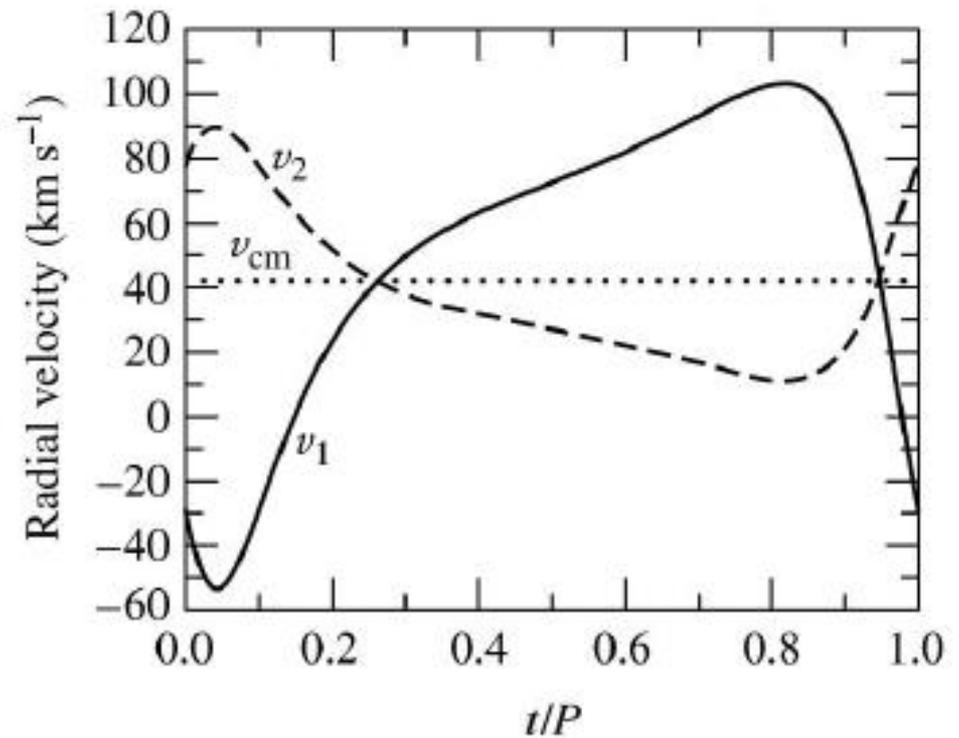


FIGURE 7.5 The orbital paths and radial velocities of two stars in circular orbits ($e = 0$). In this example, $M_1 = 1 M_\odot$, $M_2 = 2 M_\odot$, the orbital period is $P = 30$ d, and the radial velocity of the center of mass is $v_{cm} = 42 \text{ km s}^{-1}$. v_1 , v_2 , and v_{cm} are the velocities of Star 1, Star 2, and the center of mass, respectively. (a) The plane of the circular orbits lies along the line of sight of the observer. (b) The observed radial velocity curves.



(a)



(b)

FIGURE 7.6 The orbital paths and radial velocities of two stars in elliptical orbits ($e = 0.4$). As in Fig. 7.5, $M_1 = 1 M_\odot$, $M_2 = 2 M_\odot$, the orbital period is $P = 30$ d, and the radial velocity of the center of mass is $v_{cm} = 42$ km s⁻¹. In addition, the orientation of periastron is 45°. v_1 , v_2 , and v_{cm} are the velocities of Star 1, Star 2, and the center of mass, respectively. (a) The plane of the orbits lies along the line of sight of the observer. (b) The observed radial velocity curves.

Velocidade da estrela em órbita circular

semi-eixo: a ; período: P ; velocidade orbital: v ; velocidade radial: v_r

$$\frac{m_1}{m_2} = \frac{a_2}{a_1}$$

$$v = \frac{2\pi a}{P}$$

$$\frac{m_1}{m_2} = \frac{v_2}{v_1}$$

$$\frac{m_1}{m_2} = \frac{v_{2r}/\sin i}{v_{1r}/\sin i} = \frac{v_{2r}}{v_{1r}}$$

$$v_{1r} = v_1 \sin i$$

$$v_{2r} = v_2 \sin i$$

$$v_1 = \frac{v_{1r}}{\sin i}$$

Determinar o tamanho da órbita em função das velocidades

$$v = \frac{2\pi a}{P}$$



$$a_1 = \frac{P v_1}{2\pi}$$

$$a_2 = \frac{P v_2}{2\pi}$$

$$a = a_1 + a_2 = \frac{P}{2\pi} (v_1 + v_2)$$

$$a = a_1 + a_2 = \frac{P}{2\pi \text{seni}} (v_{1r} + v_{2r})$$

$$v_{1r} = v_1 \text{seni}$$

$$P^2 = \left[\frac{4\pi^2}{G(m_1 + m_2)} \right] a^3$$



$$(m_1 + m_2) = \left[\frac{4\pi^2}{GP^2} \right] \left[\frac{P}{2\pi \text{seni}} (v_{1r} + v_{2r}) \right]^3$$

$$m_1 + m_2 = \left[\frac{4\pi^2}{GP^2} \right] \frac{P^3}{8\pi^3 \text{sen}^3 i} (v_{1r} + v_{2r})^3$$

Se uma delas não for visível, isolamos v_{1r}

$$m_1 + m_2 = \frac{P}{2\pi G \text{sen}^3 i} \frac{v_{1r}^3}{\left(1 + \frac{v_{2r}}{v_{1r}}\right)^3}$$

$$\frac{m_1}{m_2} = \frac{v_{2r}}{v_{1r}}$$

$$m_1 + m_2 = \frac{P}{2\pi G \text{sen}^3 i} \frac{v_{1r}^3}{\left(1 + \frac{m_1}{m_2}\right)^3}$$

Função de Massa

$$m_1 + m_2 = \frac{P}{2\pi G \text{sen}^3 i} \frac{v_{1r}^3}{\left(\frac{m_1 + m_2}{m_2}\right)^3}$$

$$(m_1 + m_2) \left(\frac{m_2}{m_1 + m_2}\right)^3 = \frac{P}{2\pi G \text{sen}^3 i} v_{1r}^3$$

$$\frac{m_2^3}{(m_1 + m_2)^2} \text{sen}^3 i = \frac{P}{2\pi G} v_{1r}^3$$

Relação Massa-Luminosidade

→ Com base na distância podemos determinar as massas das binárias.

→ O fluxo de radiação indica a luminosidade das estrelas.

Quando colocamos num gráfico as massas e as luminosidades dos sistemas binários, temos uma correlação bem definida, chamada **relação Massa-Luminosidade (M-L)**.

A relação M-L das estrelas normais da sequência principal é dada por:

$$\frac{L}{L_{\odot}} = \left(\frac{M}{M_{\odot}} \right)^{\alpha}$$

Relação Massa-Luminosidade (cont.)

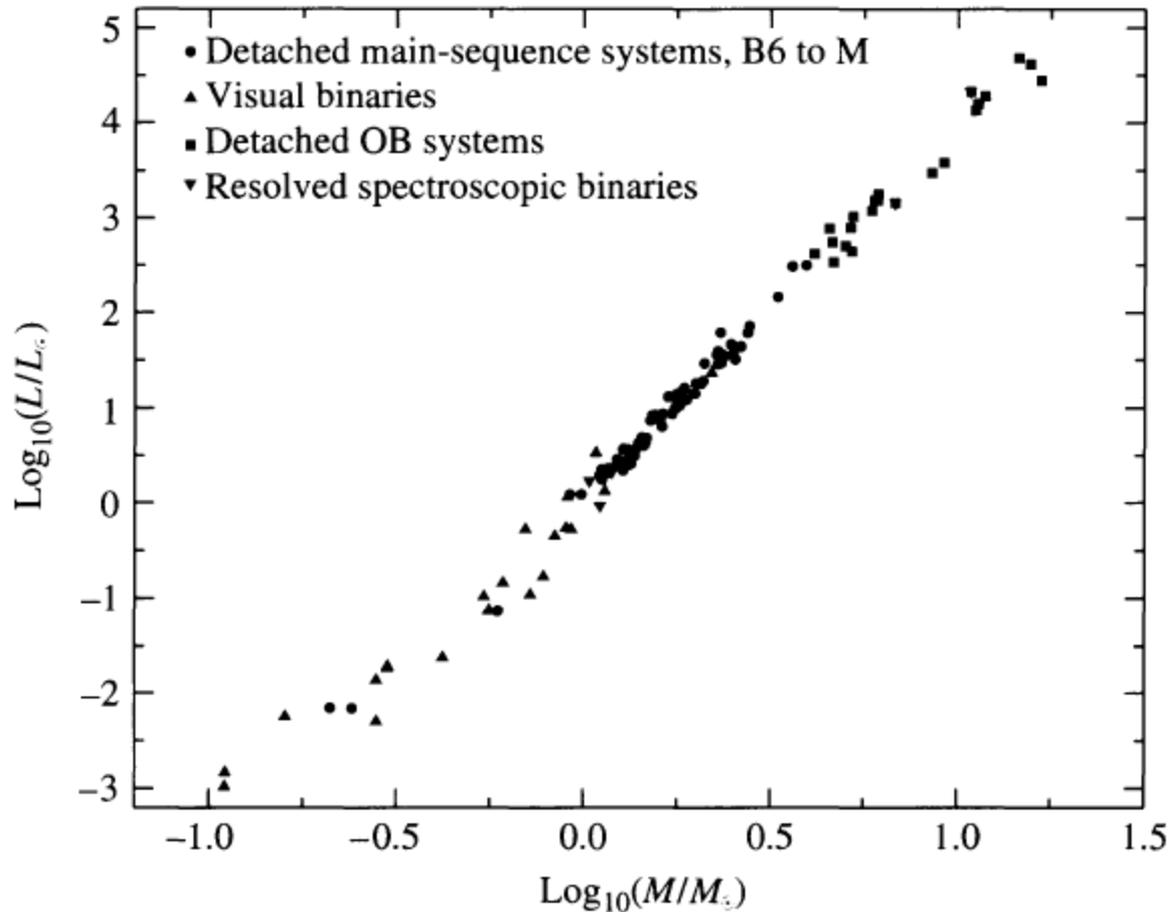
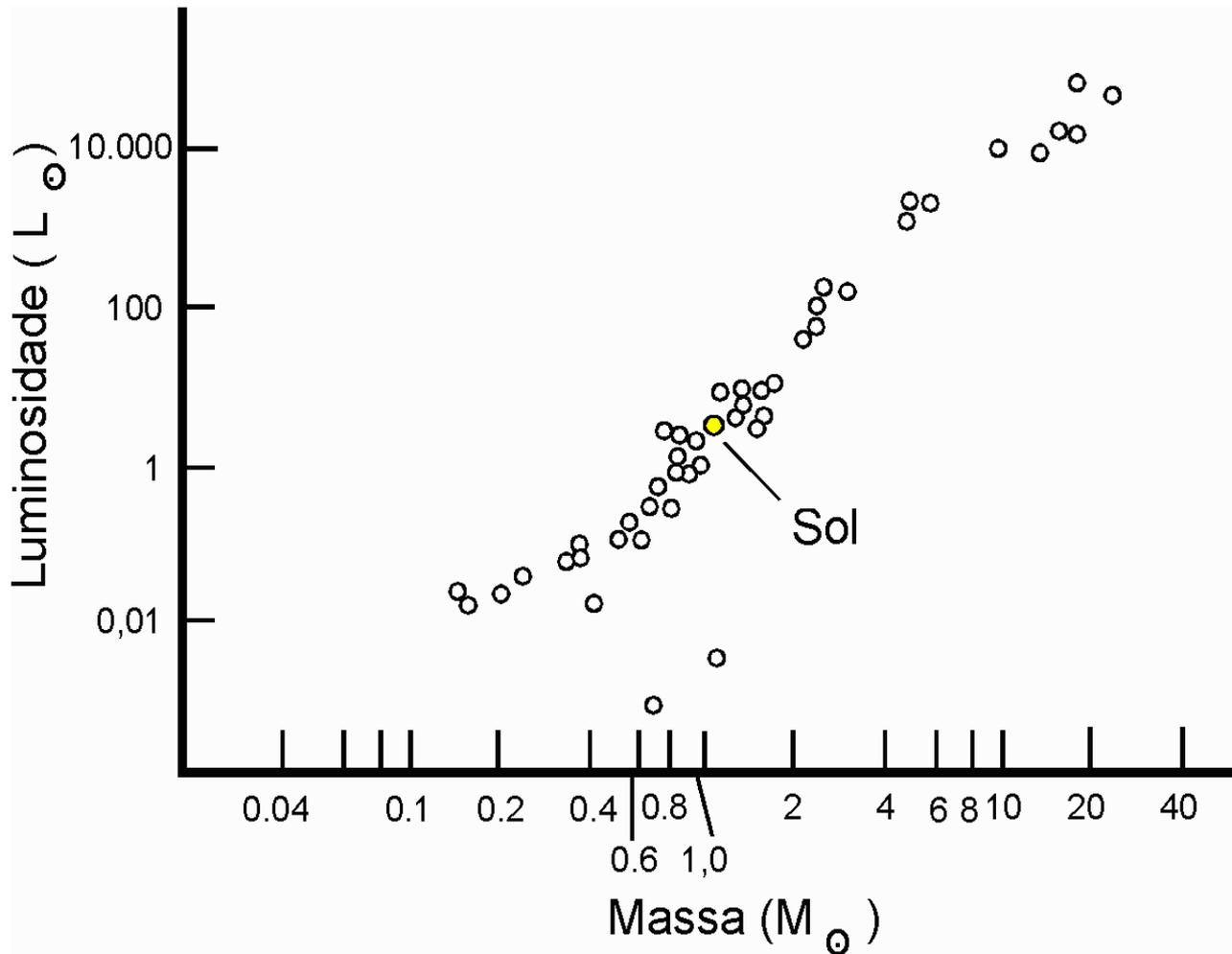


FIGURE 7.7 The mass–luminosity relation. (Data from Popper, *Annu. Rev. Astron. Astrophys.*, 18, 115, 1980.)

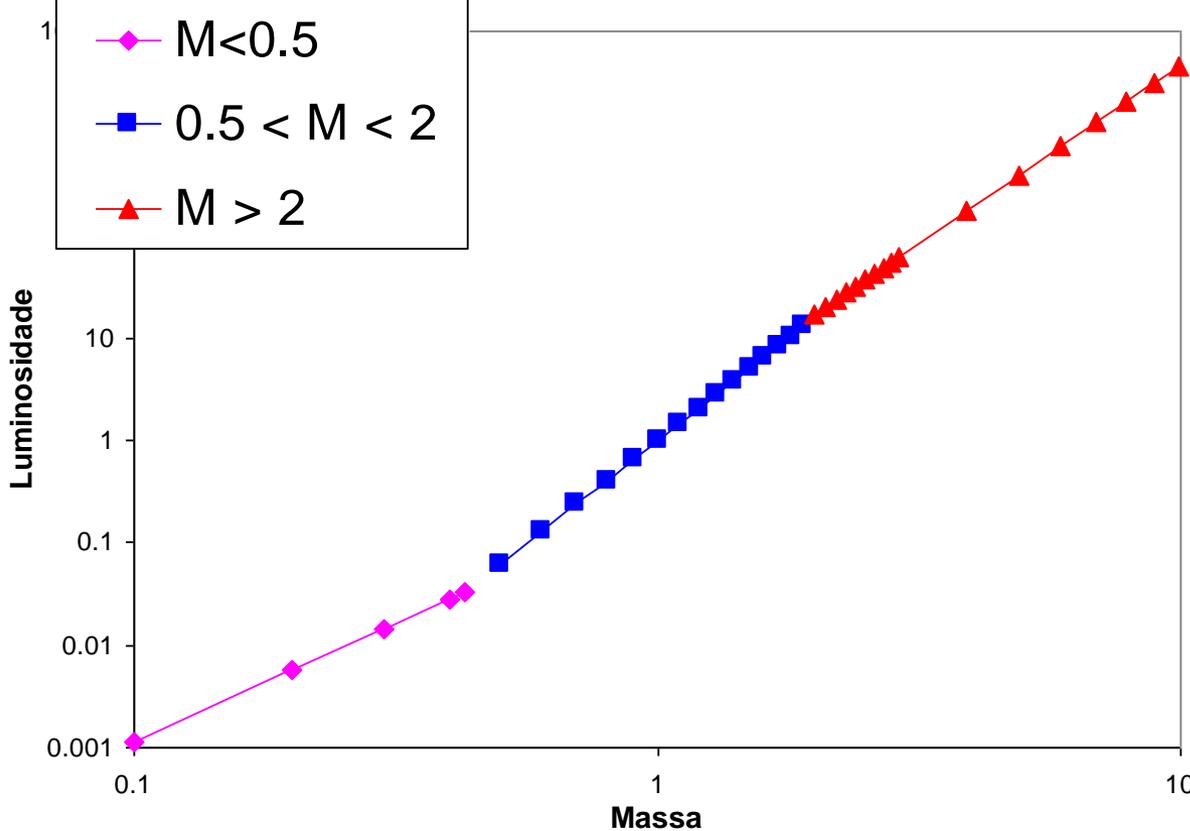


$$\frac{L}{L_{\odot}} = \left(\frac{M}{M_{\odot}} \right)^{\alpha}$$

O índice α depende da estrutura interna da estrela, opacidade das atmosferas estelares e temperatura.

Relação Massa/ Luminosidade

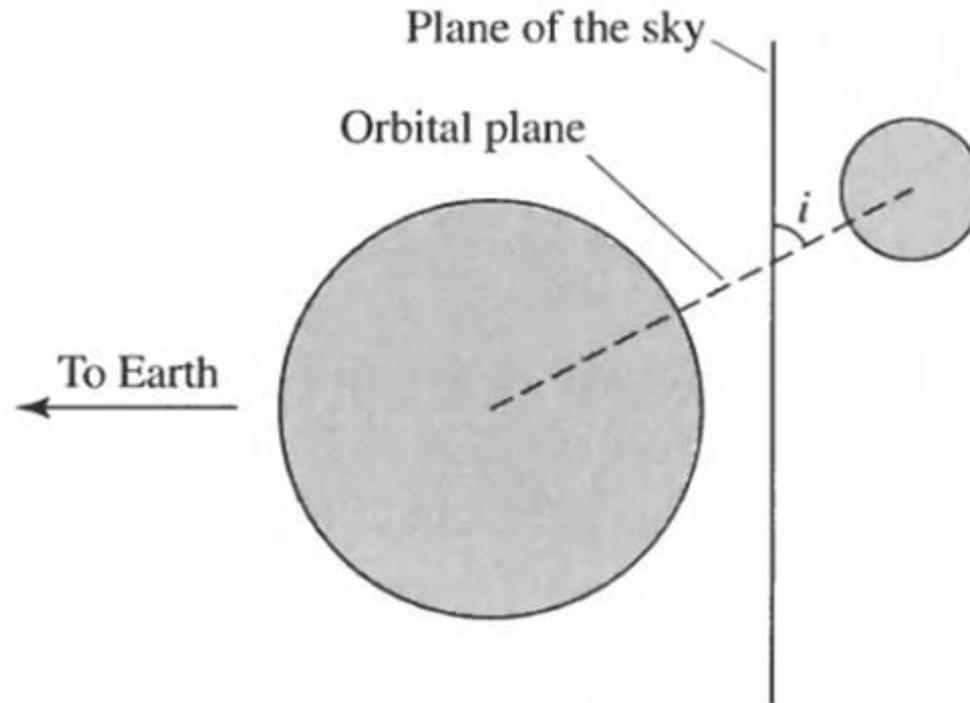
$$\frac{L}{L_{\odot}} = \left(\frac{M}{M_{\odot}} \right)^{\alpha}$$



- $\alpha \sim 3.5$ (altas M & L)
- $\alpha \sim 4$ ($\sim M_{\odot}$ & L_{\odot})
- $\alpha \sim 2.3$ (baixas M & L)

Diferenças entre estrelas
de alta e de baixa massa

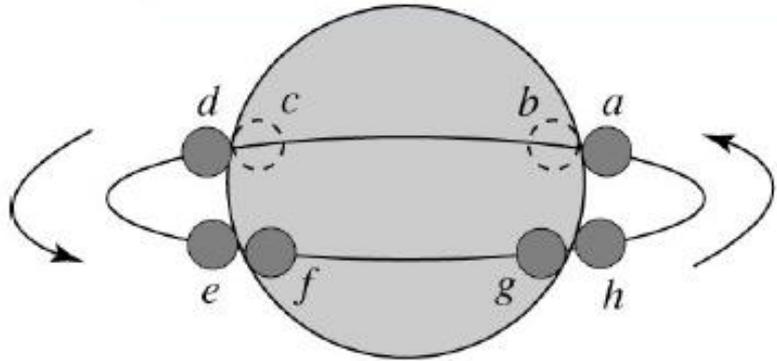
Determinação de raios e razões de temperatura por meio de eclipses



→ Eclipses ocorrem quando $i = 90^\circ$

→ Para $i = 75^\circ$, o erro em $(m_1 + m_2)$ é de 10% (diminui com fator $(\sin i)^3$).

- inclinação $i = 90^\circ$
- Velocidade relativa v

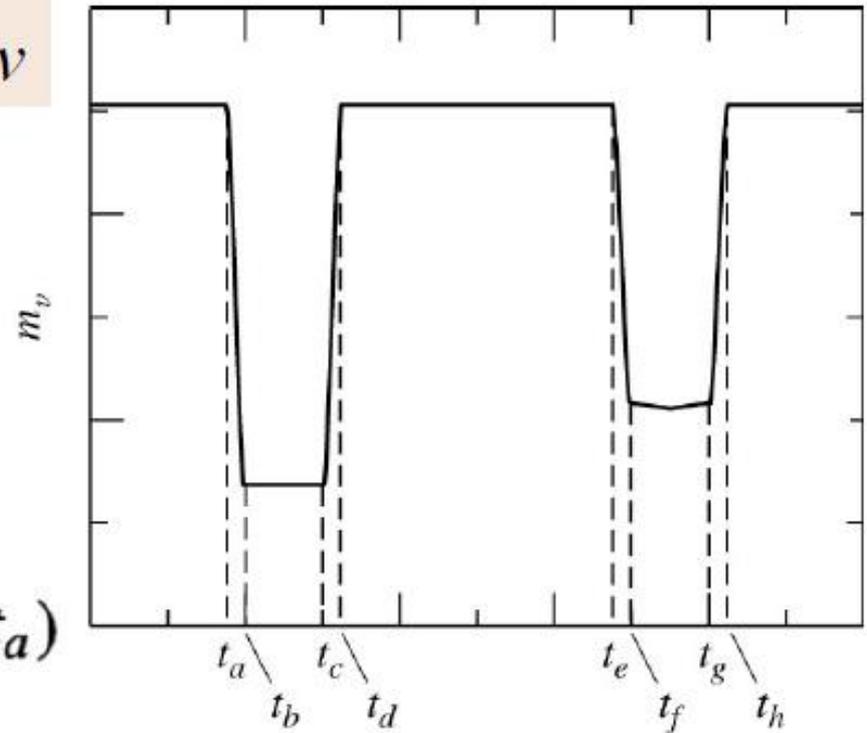


Raio da estrela pequena (small): $r_s = \frac{v}{2} (t_b - t_a)$

Raio da estrela grande (large): $r_\ell = \frac{v}{2} (t_c - t_a) = r_s + \frac{v}{2} (t_c - t_b)$

$v = v_s + v_\ell$ is the *relative* velocity of the two stars

FIGURE 7.9 The light curve of an eclipsing binary for which $i = 90^\circ$. The times indicated on the light curve correspond to the positions of the smaller star relative to its larger companion. It is assumed in this example that the smaller star is hotter than the larger one.



Se o mínimo não é constante \rightarrow estrela não é totalmente eclipsada $\rightarrow i < 90^\circ$

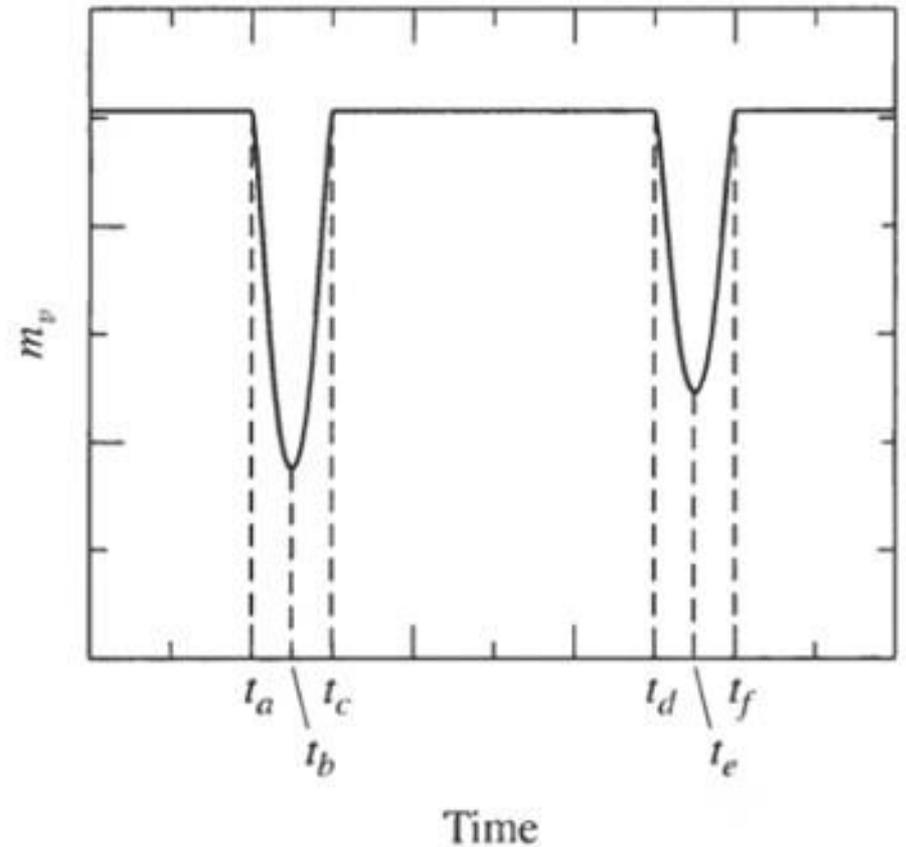
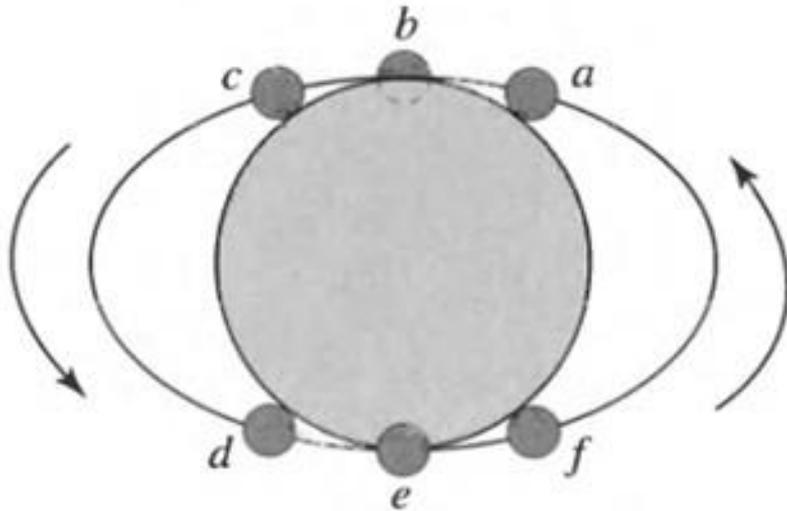


FIGURE 7.10 The light curve of a partially eclipsing binary. It is assumed in this example that the **smaller star is hotter** than its companion.

Exemplo 7.3.1. A análise do espectro de uma binária eclipsante (linhas duplas) resulta em $P = 8,6$ anos. O máximo deslocamento Doppler da linha de Balmer (656.281nm) é $\Delta\lambda_s = 0.072\text{nm}$ para a estrela menor (s) e de 0.0068nm para a estrela maior (l) Pela forma sinusoidal da curva de velocidade $\rightarrow e \sim 0$. Usando (4.39) e (7.5) encontramos a razão de massas:

$$(4.39) \quad \frac{\Delta\lambda}{\lambda_{\text{rest}}} \simeq \frac{v_r}{c}$$

s : small, l : large

$$(7.5) \quad m_1 / m_2 = v_{2r} / v_{1r} \quad \rightarrow \quad \frac{m_l}{m_s} = \frac{v_{rs}}{v_{rl}} = \frac{\Delta\lambda_s}{\Delta\lambda_l} = 10.6$$

$$\text{Se } i = 90^\circ \rightarrow \quad v_{rs} = \frac{\Delta\lambda_s}{\lambda} c = 33 \text{ km s}^{-1}$$

$$\text{Raio da órbita:} \quad a_s = \frac{v_{rs} P}{2\pi} = 1.42 \times 10^{12} \text{ m} = 9.5 \text{ AU}$$

Créditos: Prof. J. Meléndez

Da mesma maneira para a estrela maior (l):

$$v_{rl} = 3,1 \text{ km/s}, a_1 = 0,90 \text{ AU}$$

→ semi-eixo maior da massa reduzida: $a = a_s + a_1 = 10,4 \text{ AU}$

A soma das massas é obtida pela lei de Kepler:

$$m_s + m_\ell = a^3 / P^2 = 15.2 M_\odot$$

Massas resultantes: $m_s = 1.3 M_\odot$ $m_\ell = 13.9 M_\odot$

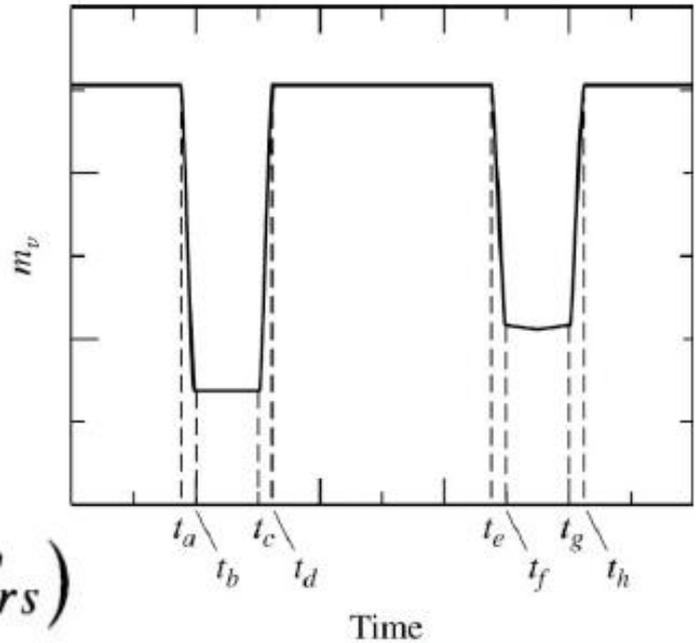
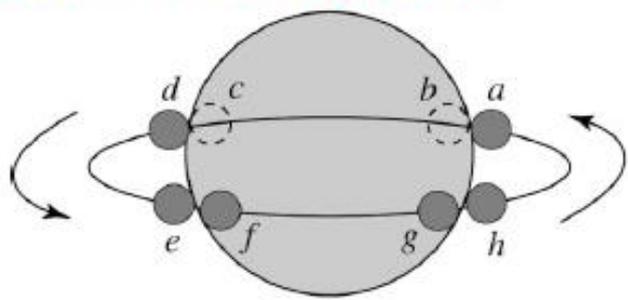
Da análise da curva de luz: $t_b - t_a = 11,7$ horas e $t_c - t_b = 164$ horas. Usando a eq. (7.8):

$$r_s = \frac{(v_{rs} + v_{r\ell})}{2} (t_b - t_a) = 7.6 \times 10^8 \text{ m} = 1.1 R_\odot$$

$$r_\ell = \frac{v}{2} (t_c - t_a) = r_s + \frac{v}{2} (t_c - t_b) \rightarrow r_\ell = 369 R_\odot$$

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Determinação de razões de temperatura por meio de eclipses



fluxo radiativo = fluxo na superfície da estrela

$$F_r = F_{\text{surf}} = \sigma T_e^4$$

$$B_0 = k (\pi r_\ell^2 F_{r\ell} + \pi r_s^2 F_{rs})$$

Eclipse Primário: $B_p = k \pi r_\ell^2 F_{r\ell}$ s: small, l: large

Secundário: $B_s = k (\pi r_\ell^2 - \pi r_s^2) F_{r\ell} + k \pi r_s^2 F_{rs}$

$$\frac{B_0 - B_p}{B_0 - B_s} = \frac{F_{rs}}{F_{r\ell}}$$

$$\frac{B_0 - B_p}{B_0 - B_s} = \left(\frac{T_s}{T_\ell} \right)^4$$

Brilho do sistema (porção total de luz detetada)

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Example 7.3.2. Further examination of the light curve of the binary system discussed in Example 7.3.1 provides information on the relative temperatures of the two stars. Photometric observations show that at maximum light the bolometric magnitude is $m_{\text{bol},0} = 6.3$, at the primary minimum $m_{\text{bol},p} = 9.6$, and at the secondary minimum $m_{\text{bol},s} = 6.6$. From Eq. (3.3), the ratio of brightnesses between the primary minimum and maximum light is

$$\frac{B_p}{B_0} = 100^{(m_{\text{bol},0} - m_{\text{bol},p})/5} = 0.048.$$

Similarly, the ratio of brightnesses between the secondary minimum and maximum light is

$$\frac{B_s}{B_0} = 100^{(m_{\text{bol},0} - m_{\text{bol},s})/5} = 0.76.$$

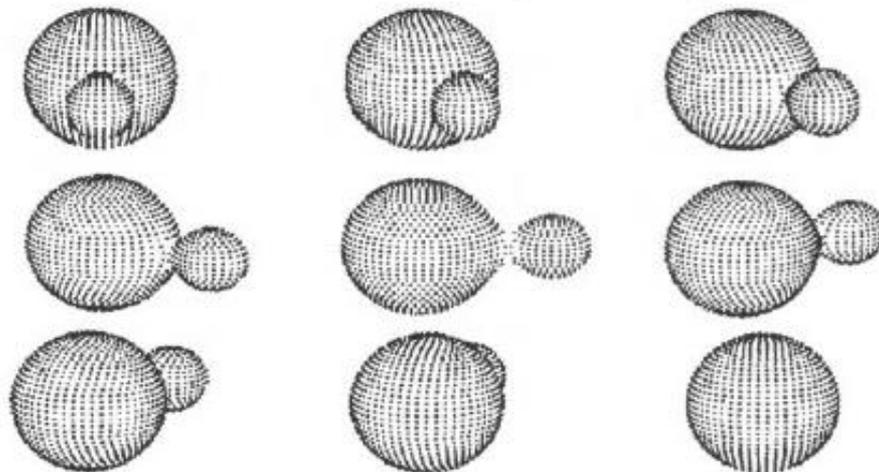
Now, by rewriting Eq. (7.10), we find that the ratio of the radiative fluxes is

$$\frac{B_0 - B_p}{B_0 - B_s} = \frac{F_{rs}}{F_{r\ell}} = 3.97.$$

Finally, from Eq. (5.18),

$$F_r = F_{\text{surf}} = \sigma T_e^4 = 1.41.$$

Modelagem de binárias por computador



Programas do livro:

<http://wps.aw.com/>

[aw_carroll_ostlie_astro_2e/](http://wps.aw.com/aw_carroll_ostlie_astro_2e/)

[48/12319/3153834.cw/index.html](http://wps.aw.com/aw_carroll_ostlie_astro_2e/48/12319/3153834.cw/index.html)

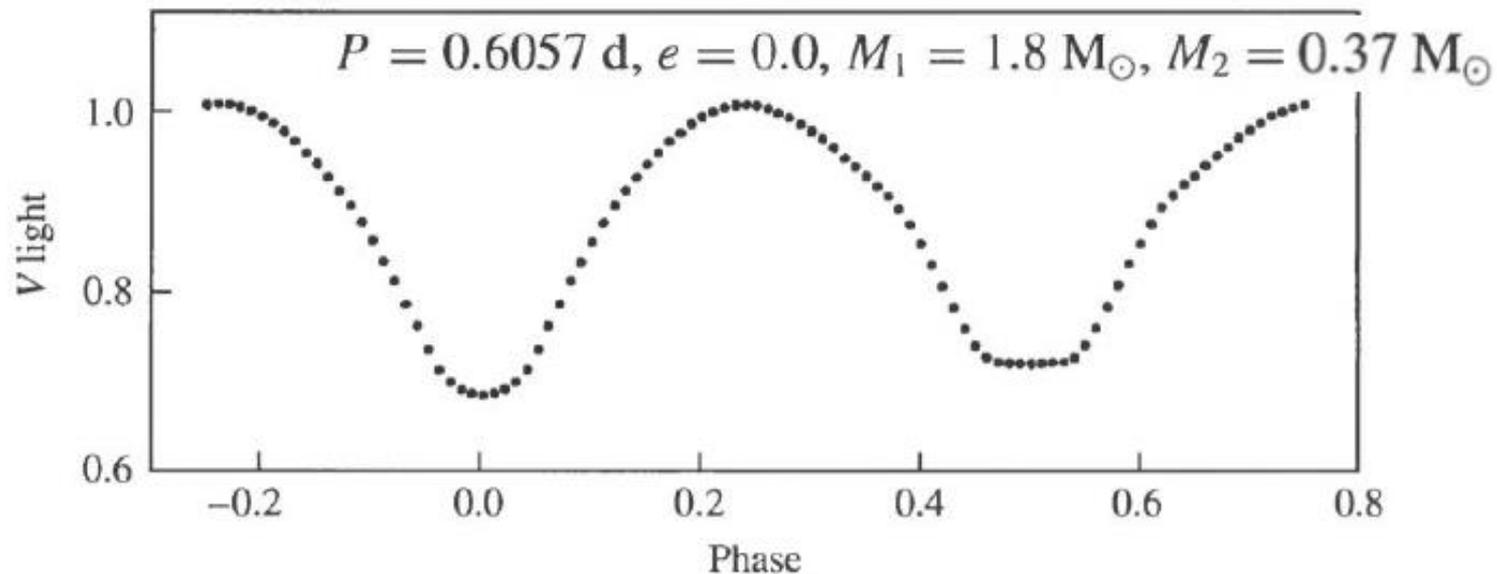
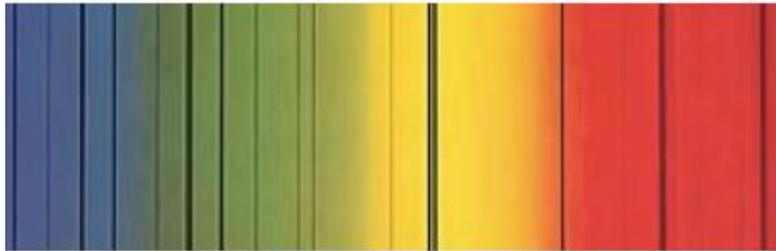


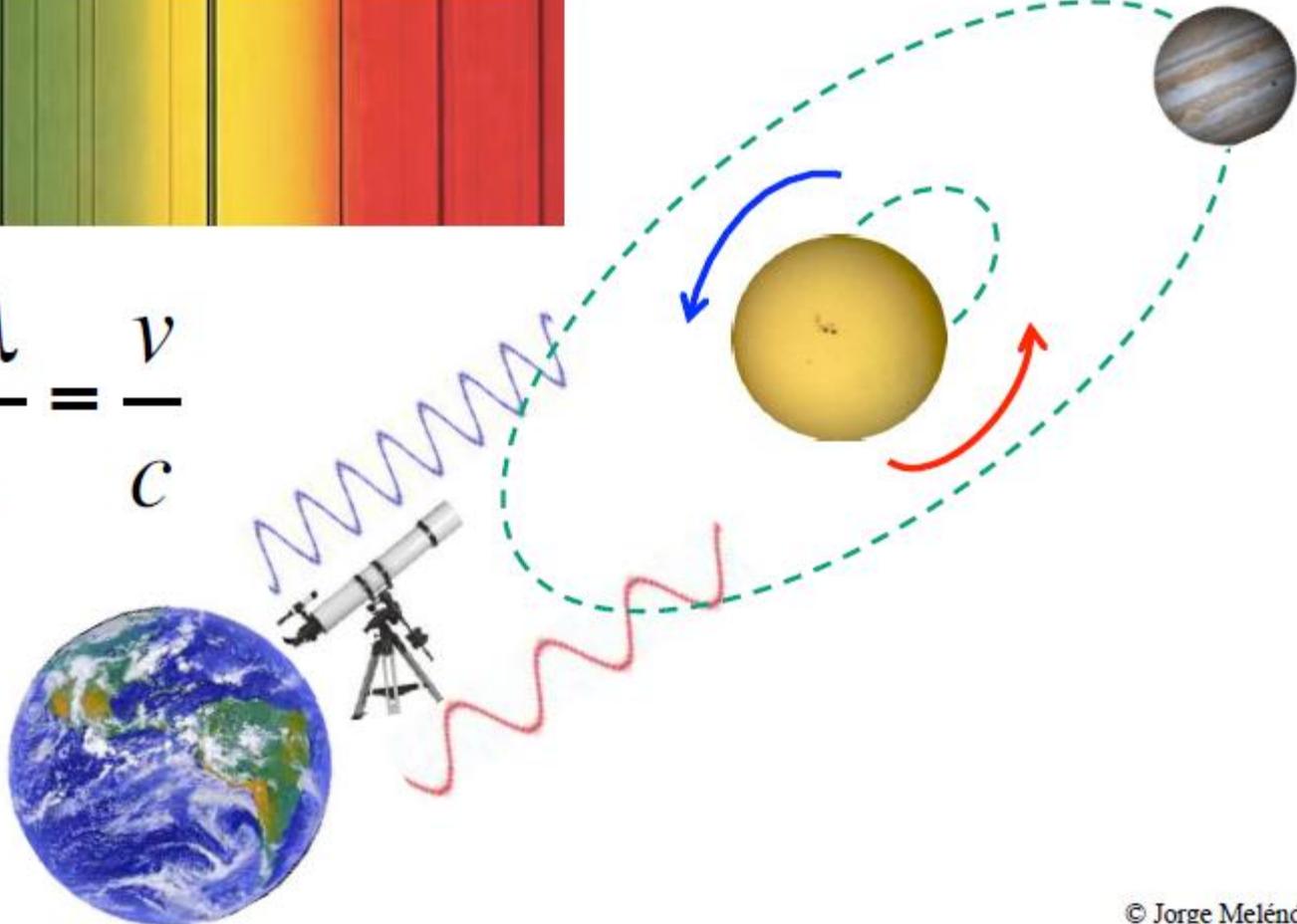
FIGURE 7.11 A synthetic light curve of RR Centauri, an eclipsing binary star system for which the two components are in close contact.

7.4 A busca por planetas extrasolares

Detecção de planetas pelo efeito Doppler

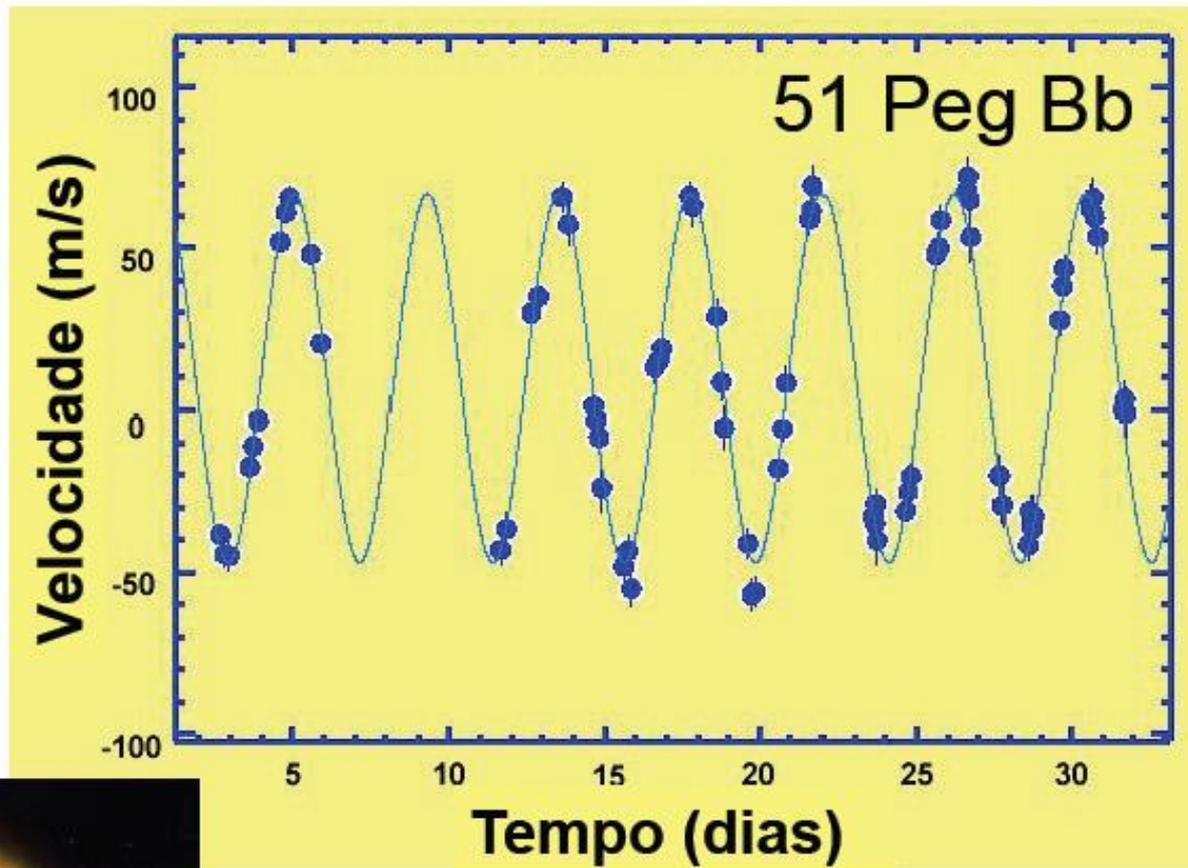


$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$



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$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$



http://www.kcvs.ca/martin/astro/au/unit7/164/chp16_4.html

Primeiro exoplaneta:
Mayor & Queloz (1995)

Créditos: Prof. J. Meléndez

Exemplo 7.4.1. **Velocidade devida a Júpiter.**

$P = 11,86$ anos, semi-eixo maior $a = 5,2$ AU, $m = 0,00095M_{\odot}$

Assumindo uma orbita circular (Júpiter tem $e = 0,0489$):

$$v_J = 2\pi a / P = 13.1 \text{ km s}^{-1}$$

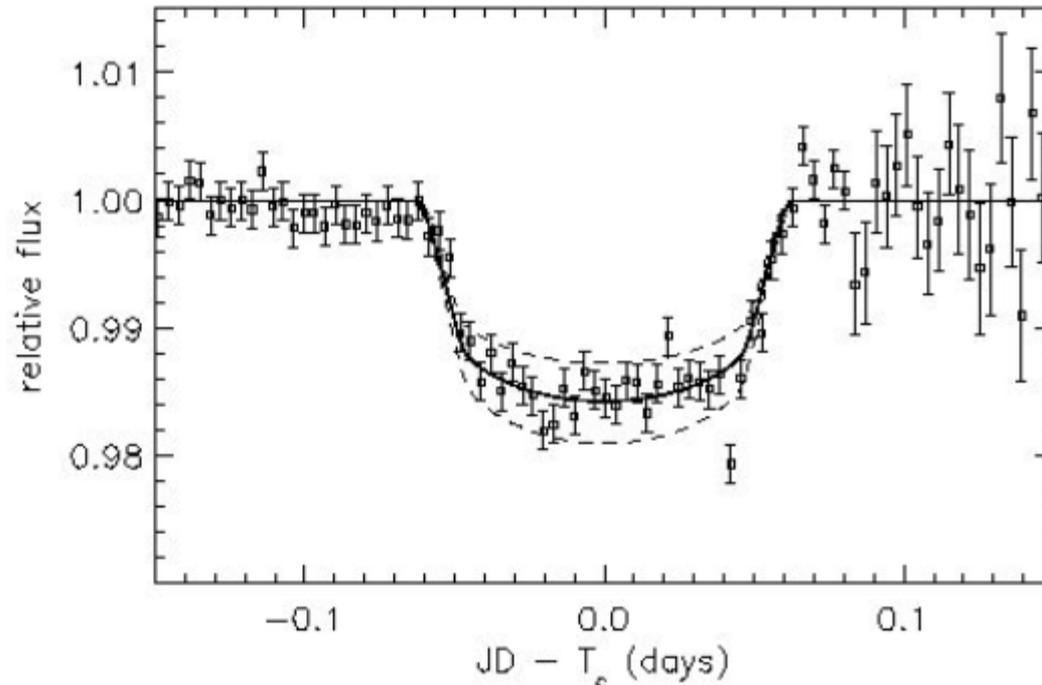
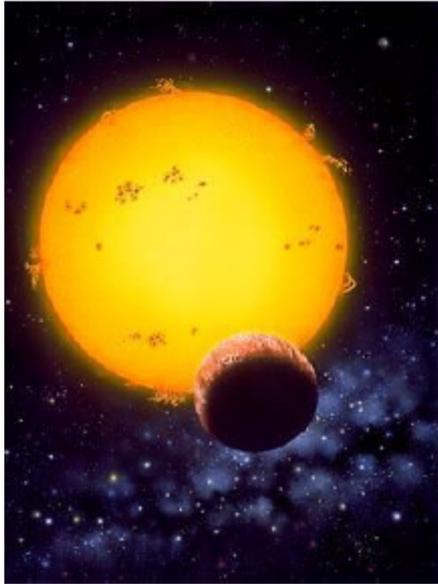
Usando: $m_1 / m_2 = v_{2r} / v_{1r}$

A velocidade do Sol: $v_{\odot} = \frac{m_J}{M_{\odot}} v_J = 12.5 \text{ m s}^{-1}$

Créditos: Prof. J. Meléndez

Detecção de exoplanetas: trânsitos

HD 209458



The Astrophysical Journal, 529:L45-L48, 2000 January 20

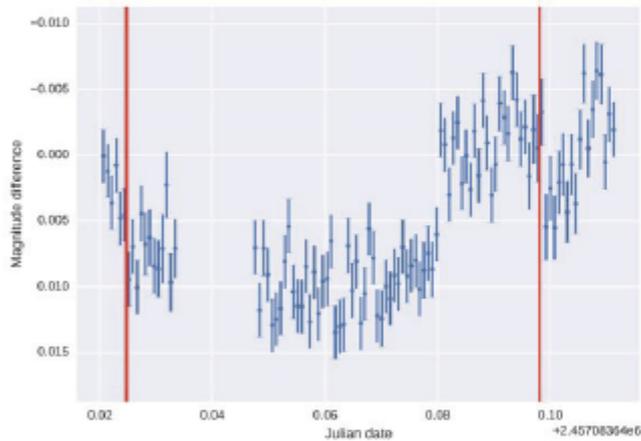
Detection of Planetary Transits Across a Sun-like Star

David Charbonneau,^{1,2} Timothy M. Brown,² David W. Latham,¹ & Michel Mayor

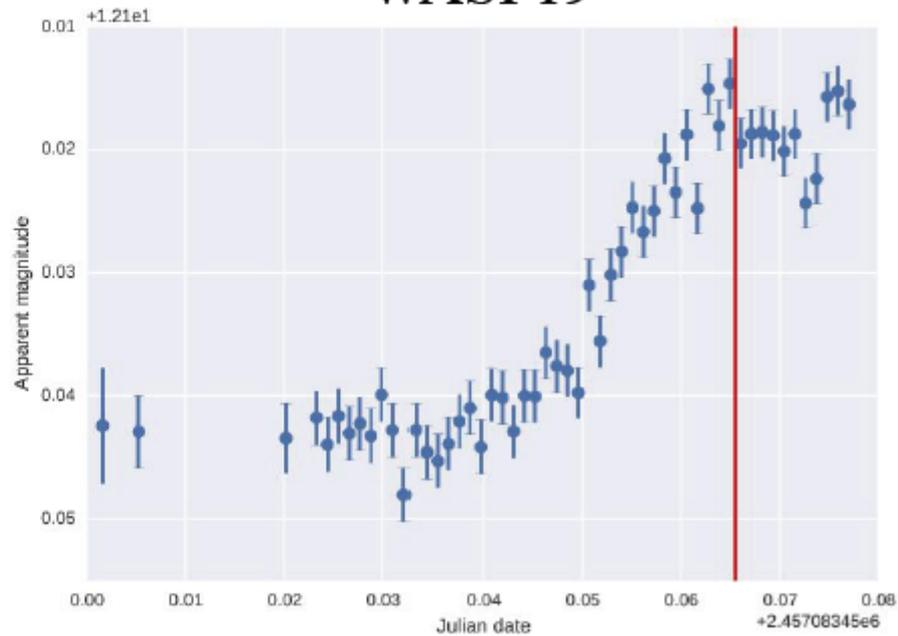
Trânsito no OPD/LNA (Brazópolis)

Detecting known exoplanets

WASP104



WASP19



Curvas de luz por Léo dos Santos (IAG/USP), telescópio 60cm (IAG)

BIBLIOGRAFIA

- Carrel & Ostlie (2007, Cap. 7)
- Karttunen et al. (1997, Cap. 4)

- Ver também

<http://slideplayer.com/slide/9211736/>

<http://slideplayer.com/slide/6341032/>

<http://slideplayer.com/slide/7116629/>