《脉冲星天文学》
暑 期 讲 习 班

PA11. Solitary and binary millisecond pulsars

讲授：徐仁新

北京大学物理学院天文学系

Lorimer-Kramer's Open Questions:

- How many pulsars are in the Galaxy and what is their birth rate?
- How are isolated millisecond pulsars produced?
- How many pulsars are in Globular clusters?
- How many pulsar planetary systems exist?
- Do the magnetic fields of isolated neutron stars decay?
- What are the minimum and maximum spin periods for radio pulsars?
- What is the relationship between core collapse in supernovae and neutron star birth properties?
- How many pulsar-black hole binaries exist?
- Are all magnetised neutron stars radio pulsars?
- How and where is the radio and high-energy emission produced?
- What is shape and structure of the radio beam?
- What is the role of propagation effects in pulsar magnetospheres?
- What is the composition of neutron star atmospheres, and how do they interact with the strong magnetic fields?

11.1 成员及其形成

- msPSR形成

超新星

↓

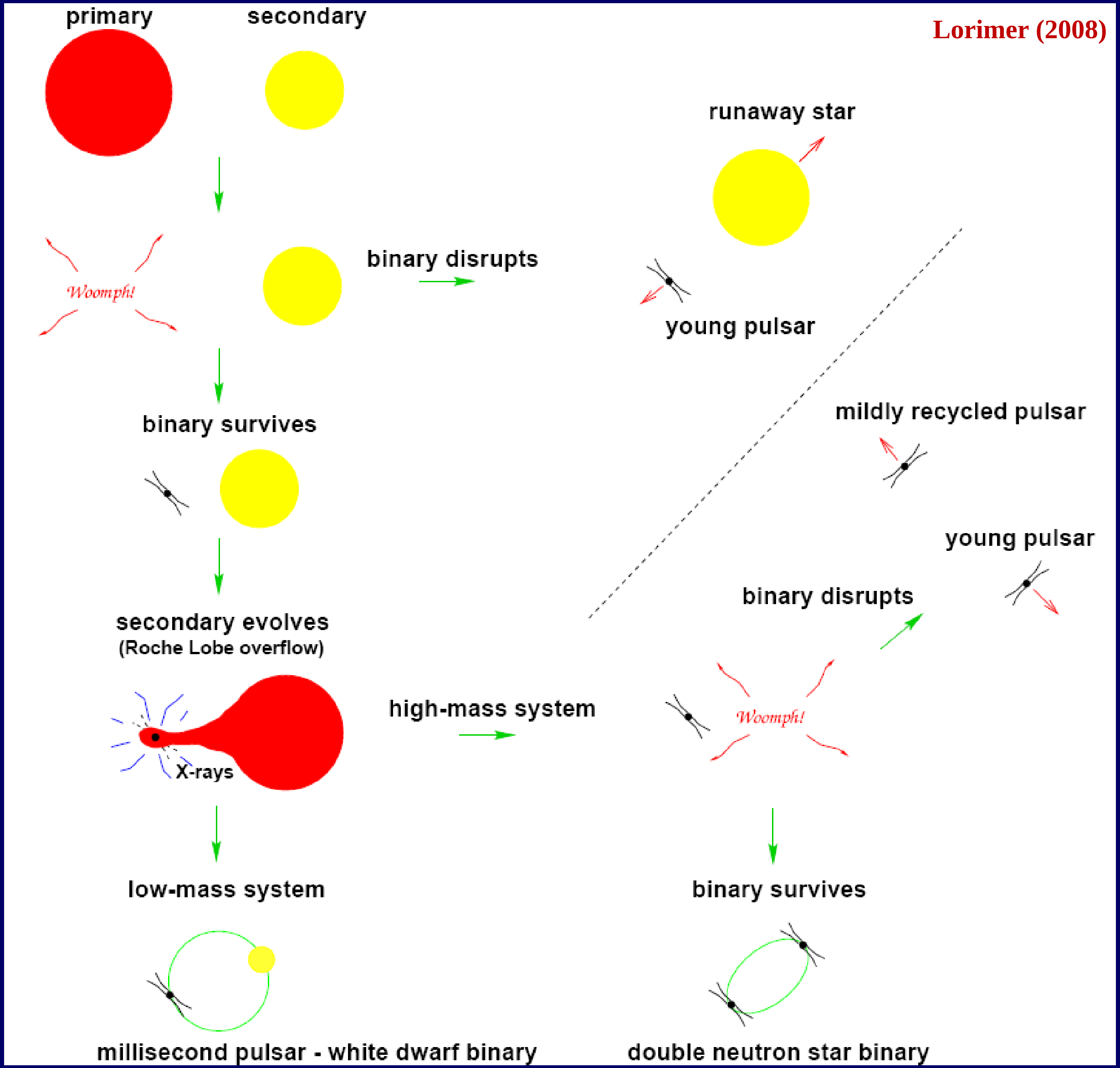
正常脉冲星

损失能量 ↓ 自转减慢

死亡脉冲星

“再加速” recycled ↓ 吸积加速

毫秒脉冲星



11.1 成员及其形成

- **PPdot图上分布**

正常脉冲星

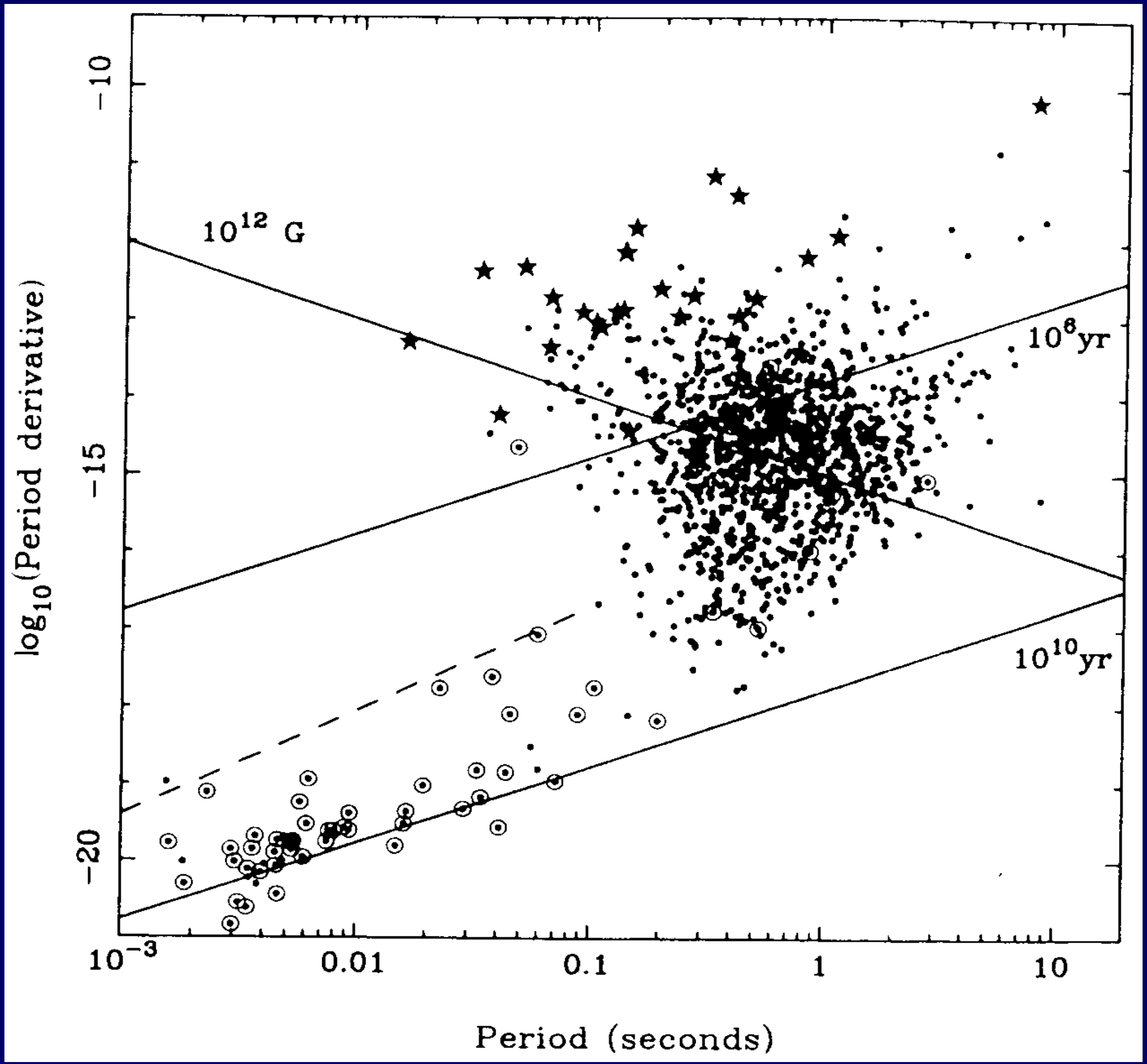
磁场 ~ 10^{12} G

年龄 ~ 10^{6} y

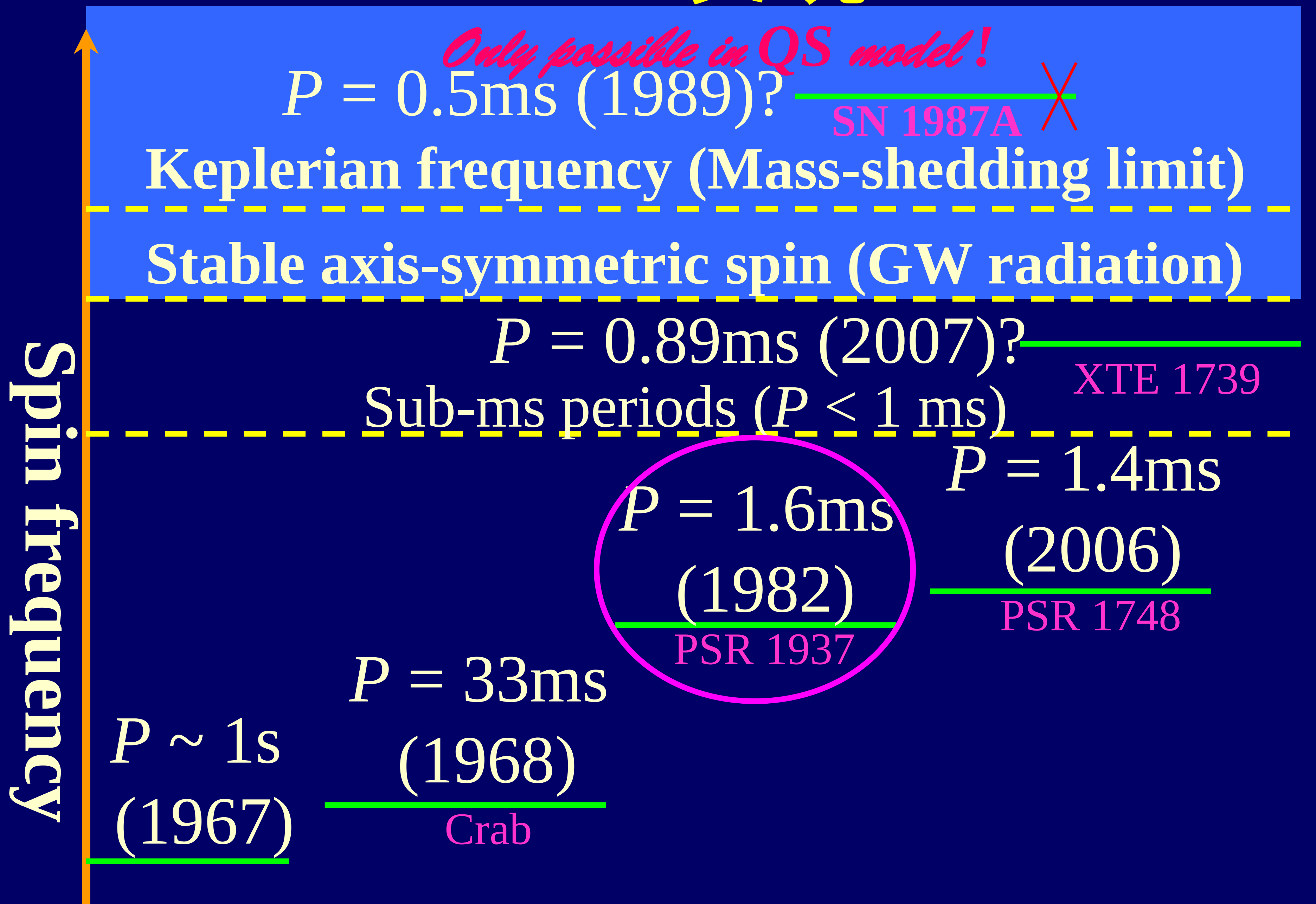
毫秒脉冲星

磁场 ~ 10^{8} G

年龄 > 10^{9} y

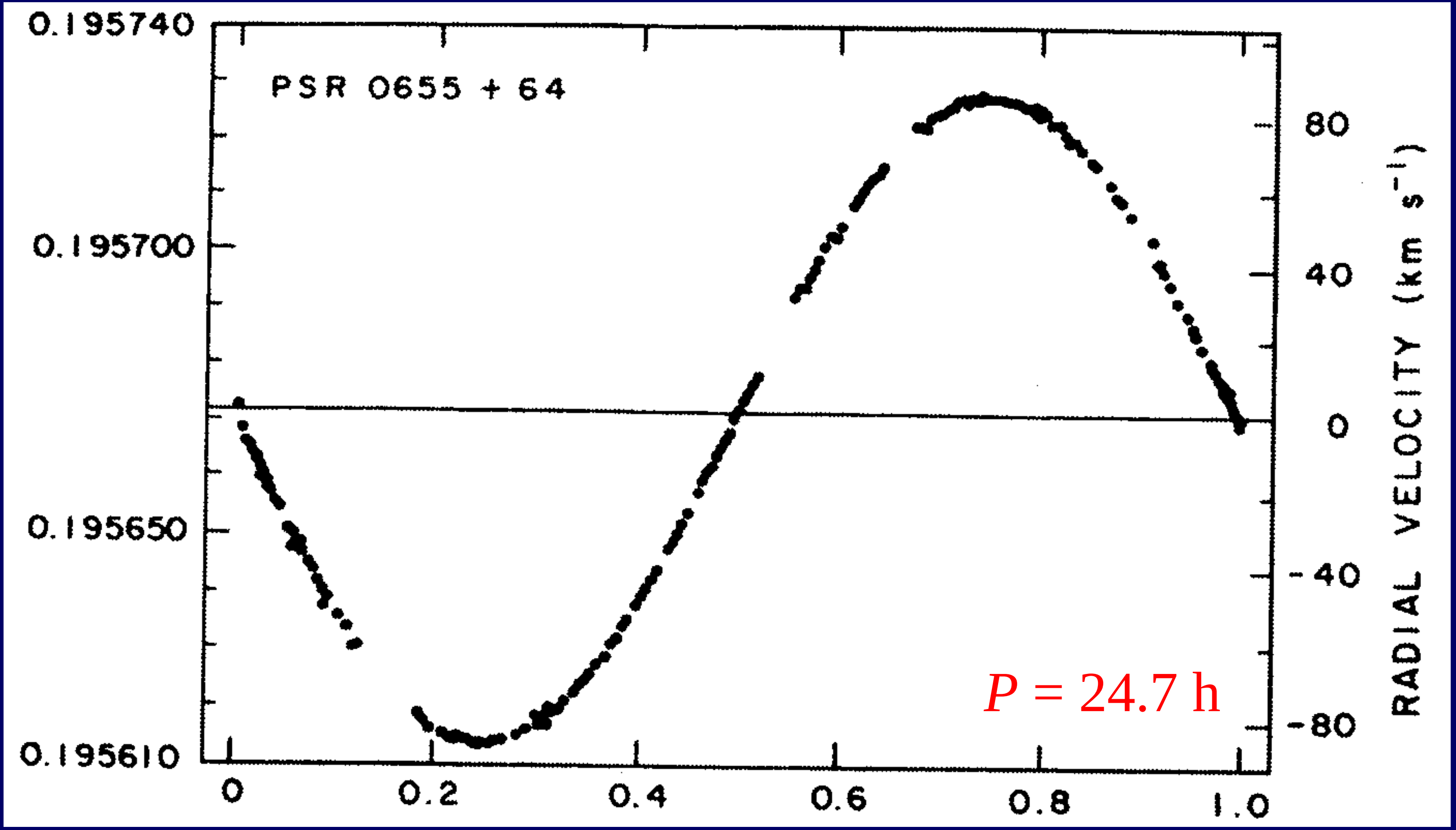


11.2 发现


Only possible in QS model!
P = 0.5ms (1989)?
SN 1987A
Keplerian frequency (Mass-shedding limit)
Stable axis-symmetric spin (GW radiation)
P = 0.89ms (2007)?
XTE 1739
Sub-ms periods (P < 1 ms)
P = 1.4ms (2006)
PSR 1748
P = 1.6ms (1982)
PSR 1937
P = 33ms (1968)
Crab
P ~ 1s (1967)
Spin frequency

11.2 发现

- 双星系统中毫秒脉冲星（例：近圆轨道）



11.3 质量的测量

考虑质量M_1、M_2两星体因引力而互相圆轨道绕转⇒ Kepler第三定律修正式：

$$\frac{M_2^{\ 3}}{(M_1+M_2)^2}=\frac{r_1^{\ 3}}{G}\left(\frac{2\pi}{P_{\rm orb}}\right)^2$$

$a_{\rm i}$

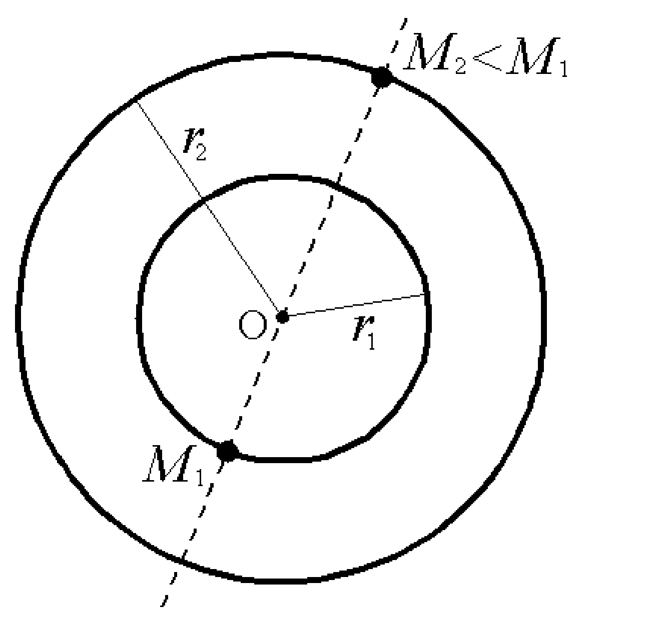
- 推广至一般的椭圆轨道：

质量函数

$$\frac{(M_2\sin i)^3}{(M_1+M_2)^2}=\frac{(a_1\sin i)^3}{G}\left(\frac{2\pi}{P_{\rm orb}}\right)^2\equiv f_1$$

$$\frac{(M_1\sin i)^3}{(M_1+M_2)^2}=\frac{(a_2\sin i)^3}{G}\left(\frac{2\pi}{P_{\rm orb}}\right)^2\equiv f_2$$

- 一颗子星的质量函数是另一颗子星质量值的下限



两质点因引力作用做圆轨道运动

11.3 质量的测量

- 利用质量函数确定伴星/脉冲星质量

$$f_{psr} = \frac{(M_c \sin i)^3}{(M_{psr} + M_c)^2}$$

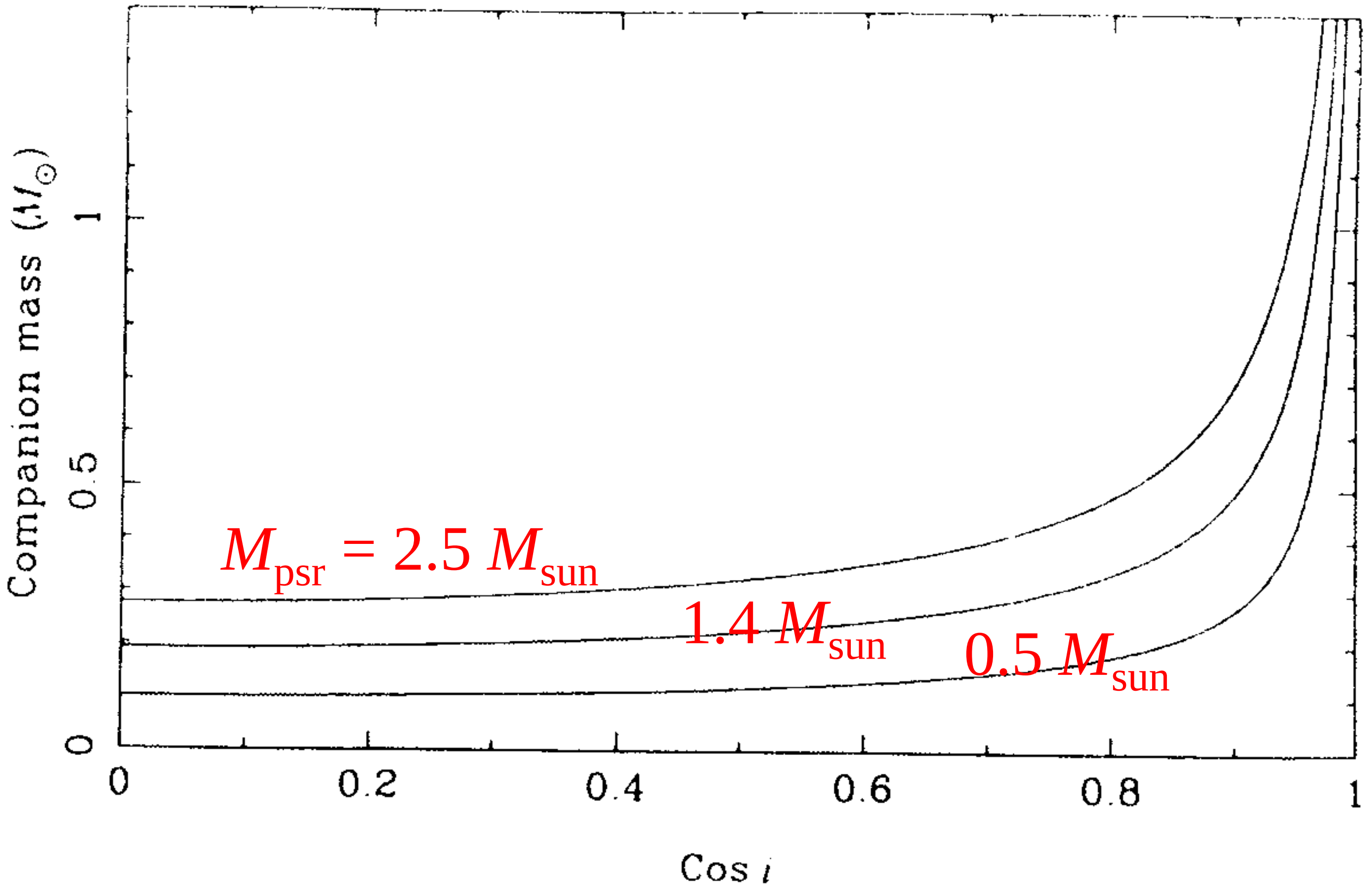
B1953+29:

$f = 0.00272 M_{sun}$

置M_{psr}=1.4 M_{sun}

则：

$M_{psr} \sim (.2\text{-}.5)\ M_{sun}$



GW radiation from PSRs

- 利用后Kepler参数确定脉冲星质量

  Post-Keplerian Parameters: ***gravity-theory dependent***

- **GR框架中：**

PSR B1913+16:

$\dot{\omega}$, γ, $\dot{P}_b$ measured

PSR J0737-3039A/B

$\dot{\omega}$, γ, r, s, $\dot{P}_b$ measured

Pulsars: ***point***-like!

$$\dot{\omega} = 3T_\odot^{2/3} \left(\frac{P_b}{2\pi}\right)^{-5/3} \frac{1}{1-e^2} (m_p + m_c)^{2/3}$$

$$\gamma = T_\odot^{2/3} \left(\frac{P_b}{2\pi}\right)^{1/3} e \frac{m_c(m_p+2m_c)}{(m_p+m_c)^{4/3}}$$

$$r = T_\odot m_c$$

$$s = \sin i = T_\odot^{-1/3} \left(\frac{P_b}{2\pi}\right)^{-5/3} x \frac{(m_p+m_c)^{2/3}}{m_c}$$

$$\dot{P}_b = -\frac{192\pi}{5} T_\odot^{5/3} \left(\frac{P_b}{2\pi}\right)^{-5/3} f(e) \frac{m_p m_c}{(m_p+m_c)^{1/3}}$$

$$\Omega_{\rm geod} = \left(\frac{2\pi}{P_b}\right)^{5/3} T_\odot^{2/3} \frac{m_c(4m_p+3m_c)}{2(m_p+m_c)^{4/3}} \frac{1}{1-e^2}$$

$$T_\odot = GM_\odot/c^3 = 4.9254909\mu s$$

11.3 质量的测量

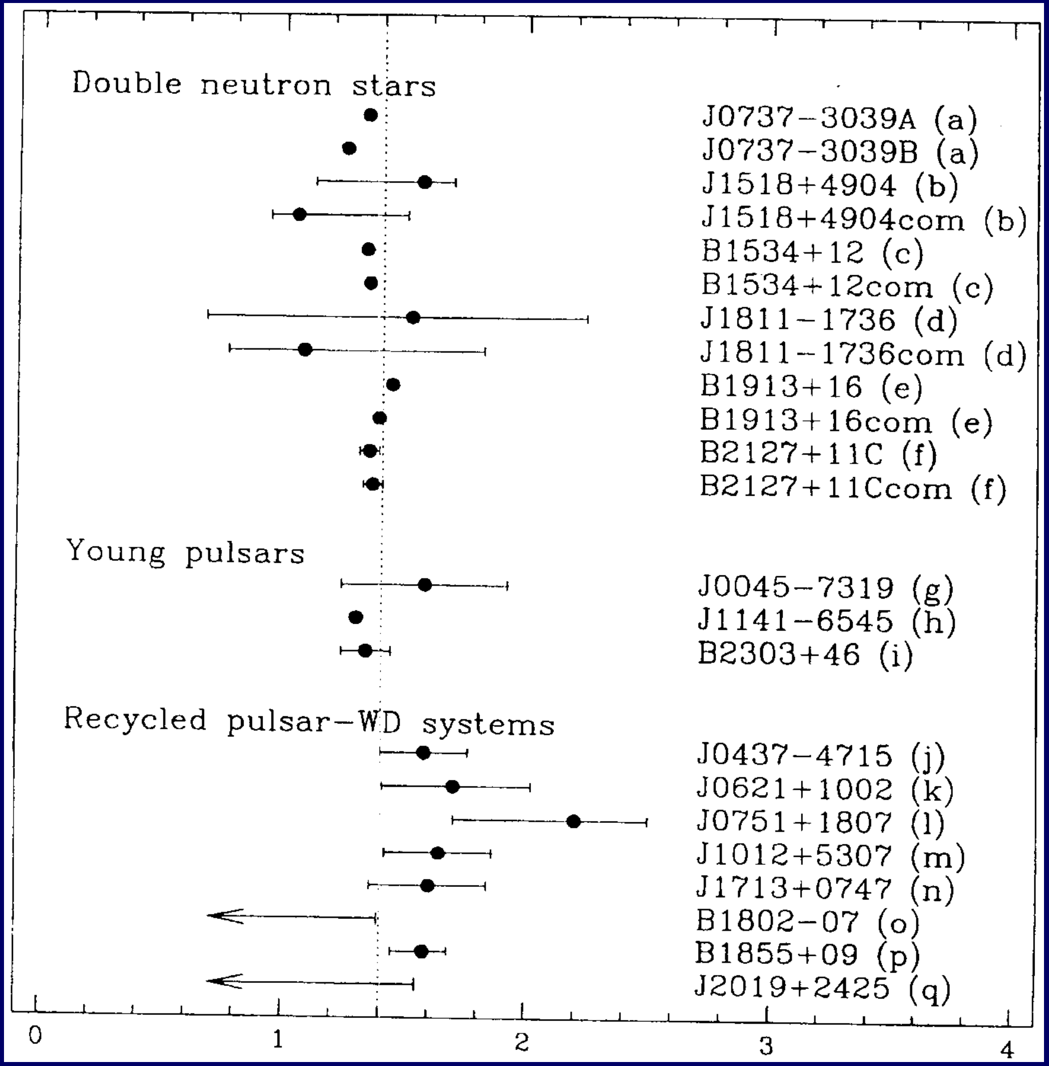
• 脉冲星质量统计

“$M_{psr} \sim 1.4\ M_{sun}$!”

真实（反映形成过程）

还是

观测效应？



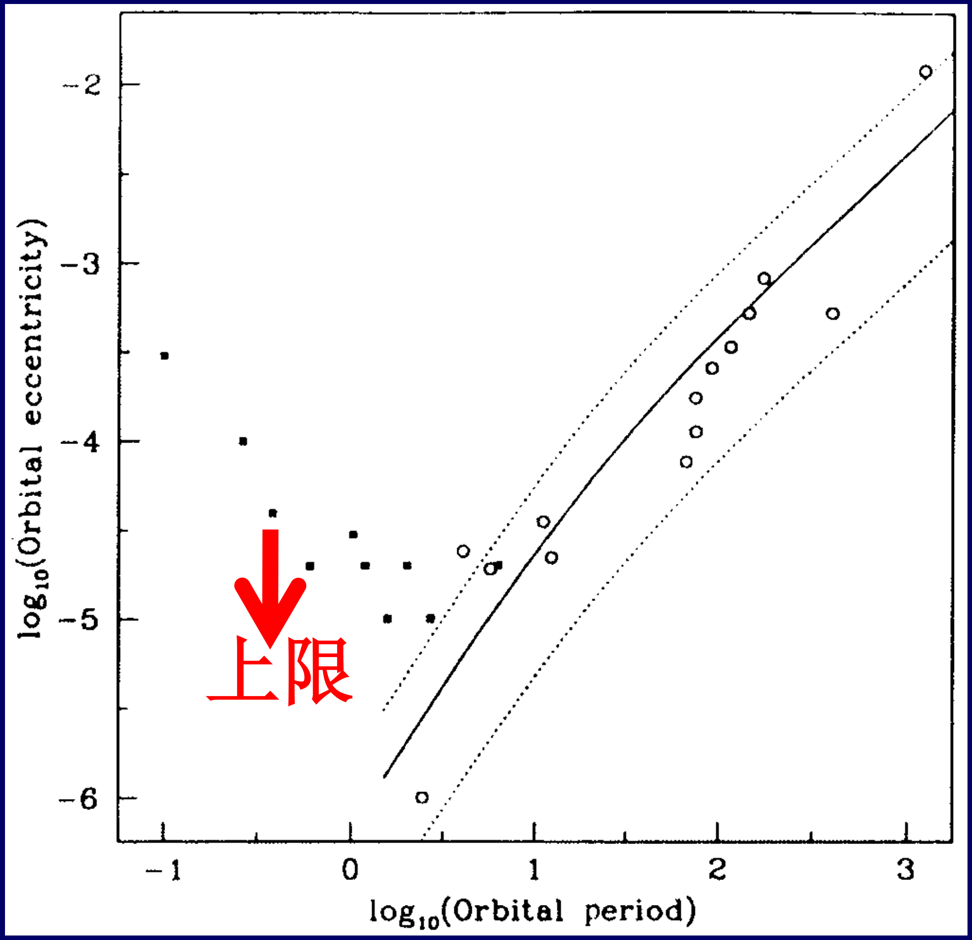
11.4 双星轨道特征

- 双星轨道周期与偏心率的统计

Phinney (1992):

考虑“白矮星+红巨星”系统

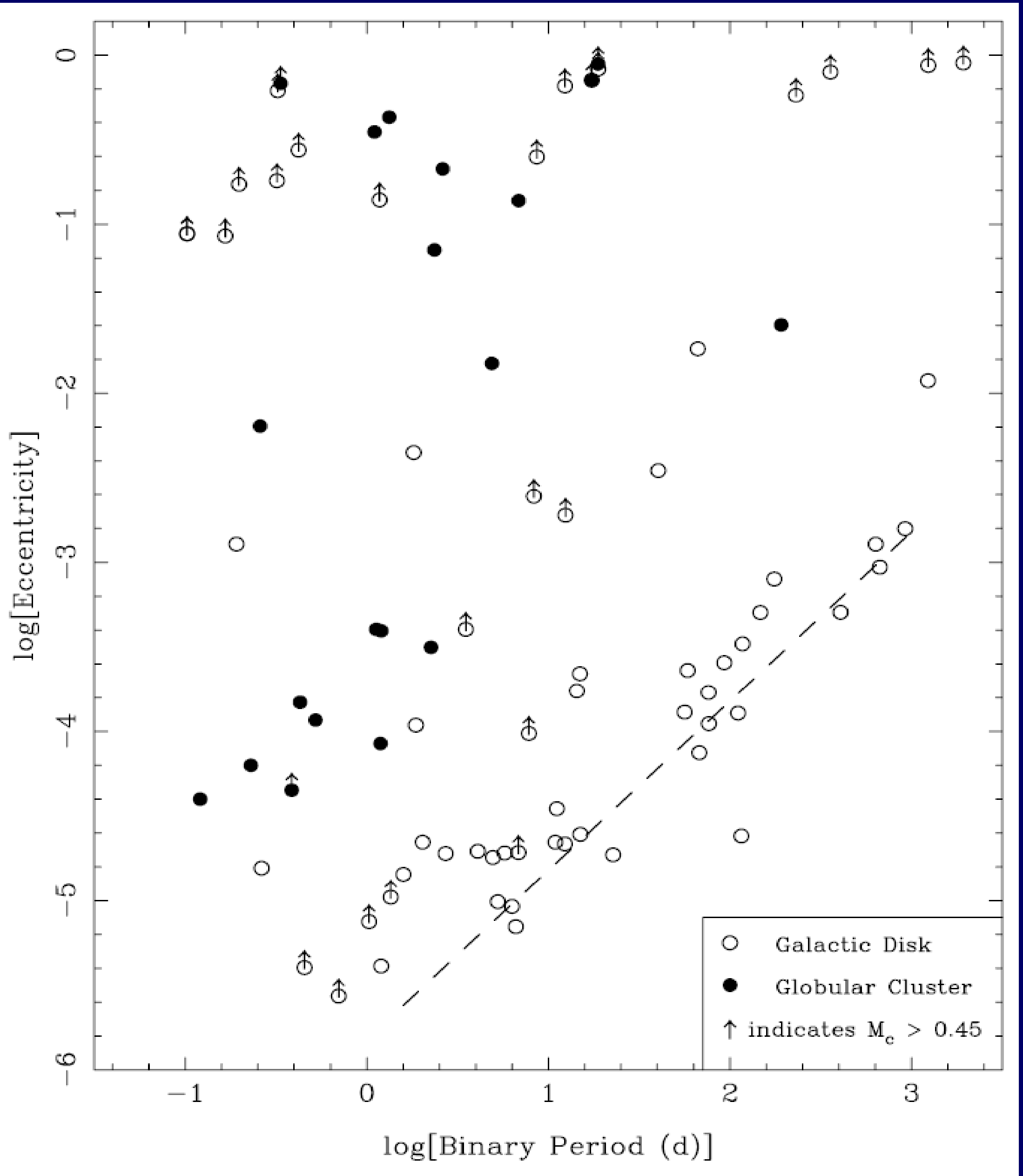
若初始轨道*e*很大，因吸积导致轨道圆化。



11.4 双星轨道特征

- 更多统计数据

Manchester (2006)

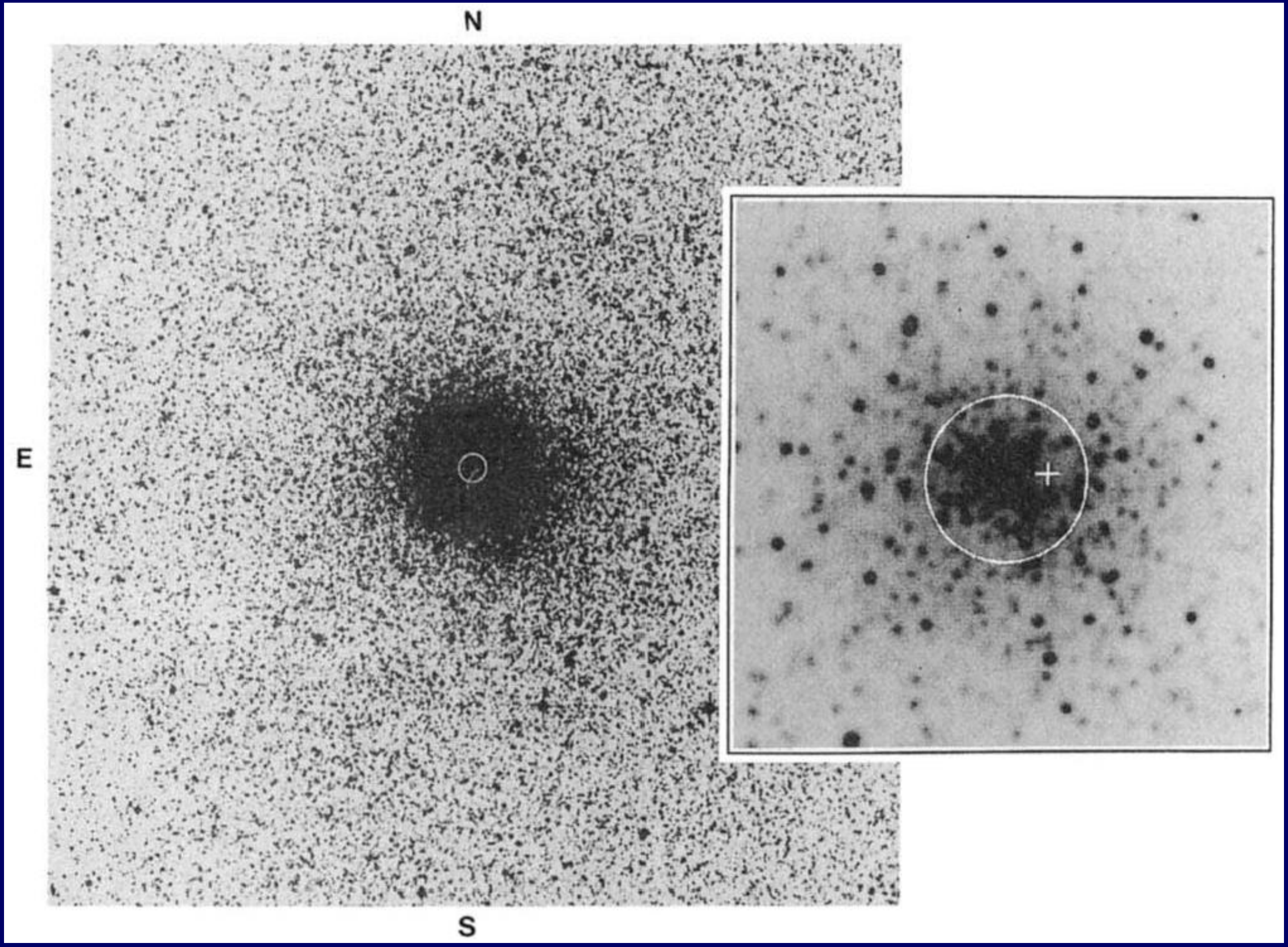


11.5 球状星团中的脉冲星

Becker et al. (1982)

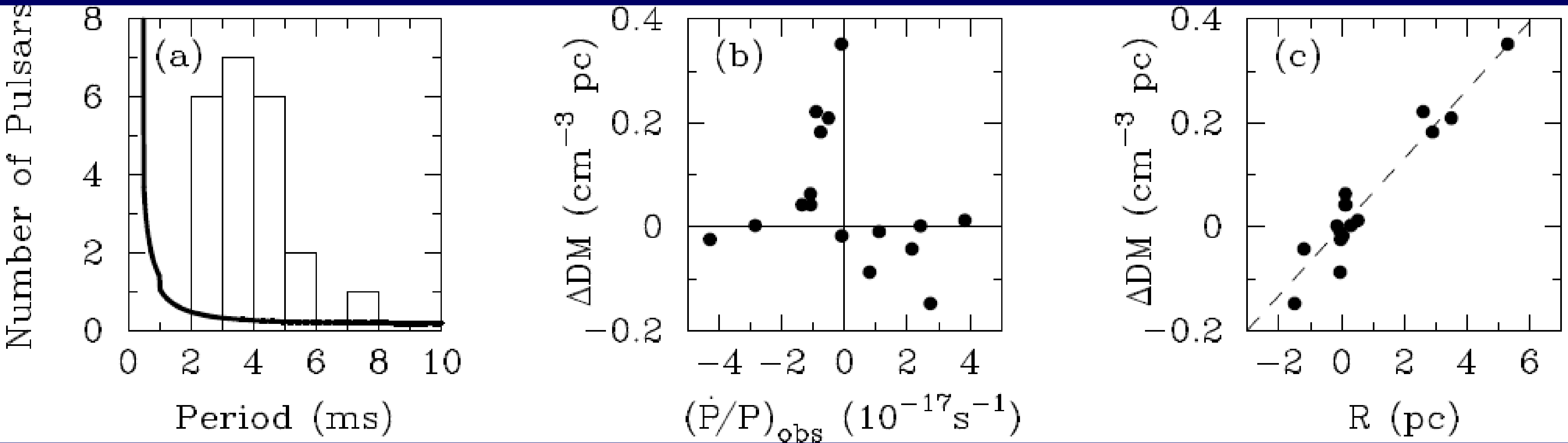
Lyne et al. (1987)：
B1821-24,
2ms,
in M28

（也是陡谱）



11.5 球状星团中的脉冲星

- **47 Tuc中发现22颗！**



- **Terzan 5中也发现21颗！**

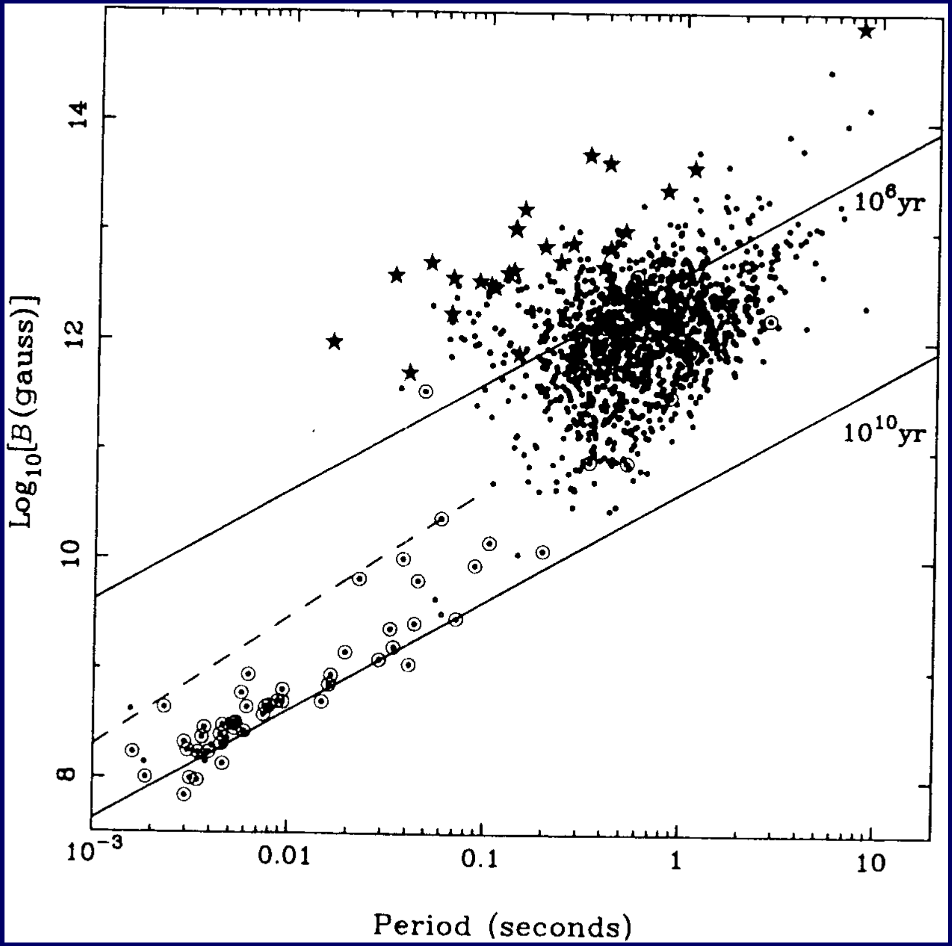
11.6 脉冲星的磁场

- 毫秒脉冲星为何拥有$10^{8\sim9}$G的磁场？
  - 正常脉冲星磁场不衰减
  - 毫秒脉冲星磁场降低~10^3倍

recycled 再加速

磁场在吸积过程中衰减了！

1. Ohmic耗散过程？
2. 吸积流磁场屏蔽？
3. 为何至~10^8G不在衰减？

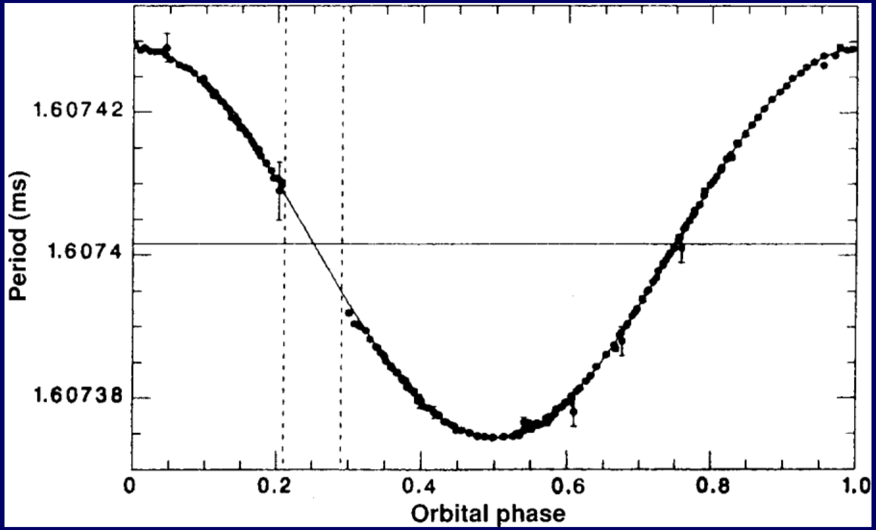


11.7 脉冲星双星系统中掩蚀

- **PSR+WD双星系统**

PSR **WD**

~10^7km ~10^4km



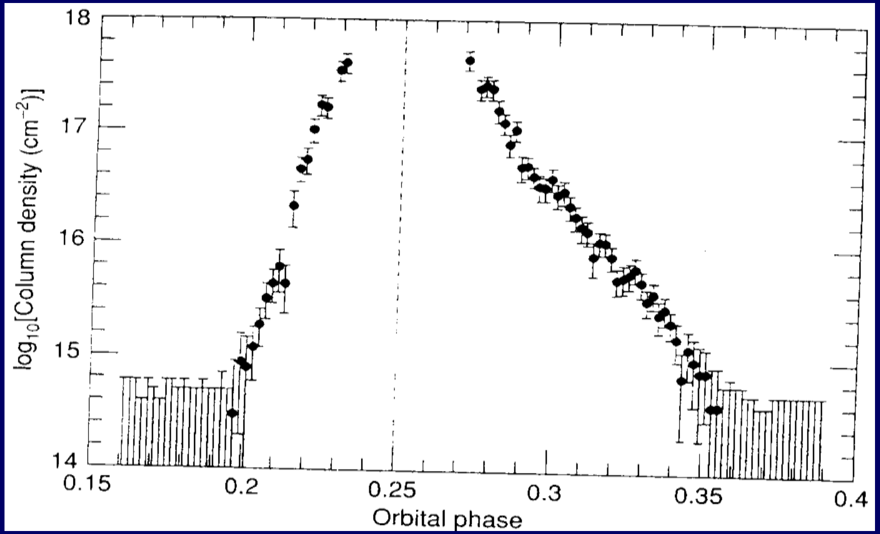
- **PSR B1957+20:**

P =1.6 ms, $P_{\rm orb}$ = 8 h

$M_{\rm wd}$ = 0.02 $M_{\rm sun}$

$R_{\rm wd\text{-}cloud}$=1.5$R_{\rm s}$ > 0.5$R_{\rm s}$

Roche lobe radius



11.8 脉冲星-主序星双星

- **J0045-7319 (SMC), 无掩蚀和DM变化**

$M_c = 9M_s$

- **B1259-63**

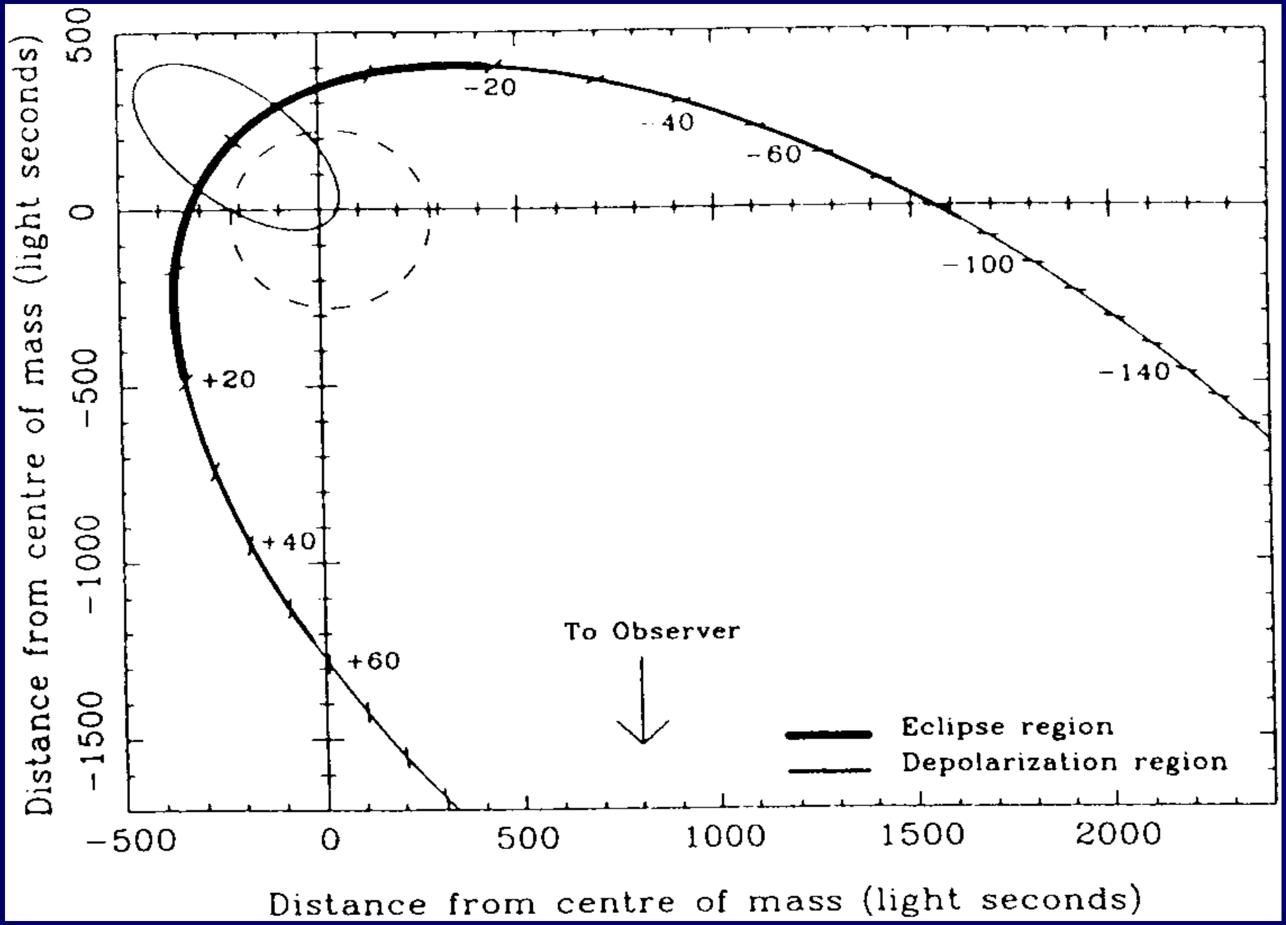
$M_c \sim 10M_s$

$R_c \sim 6R_s$

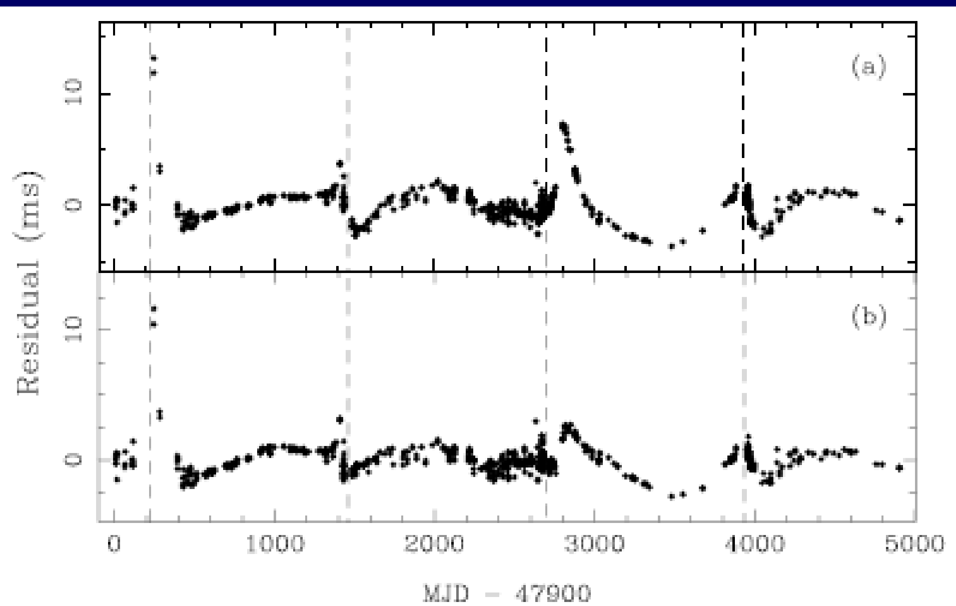
$P_{orb} \sim 3.5y$

掩蚀 ~ 20d

***x*-jump?**



11.8 脉冲星-主序星双星



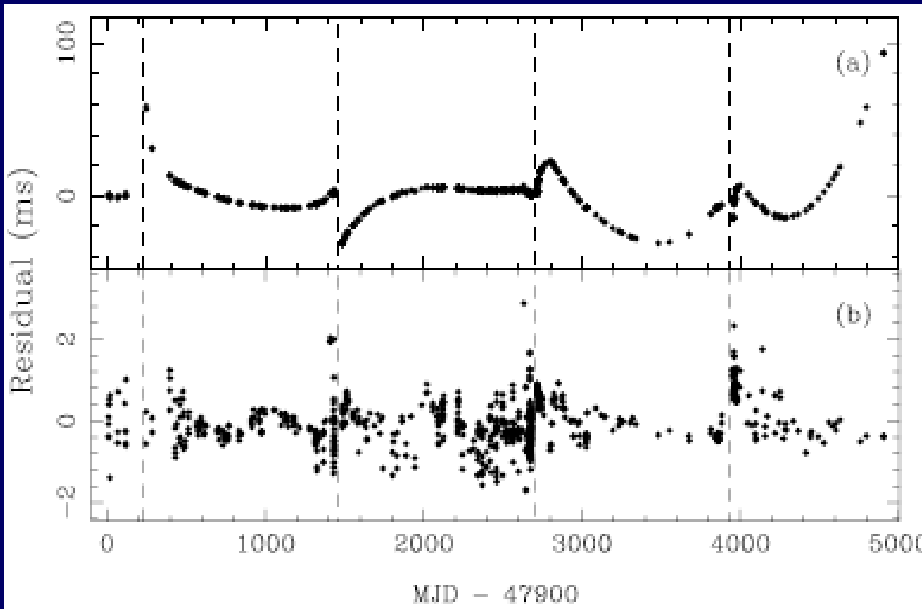


Figure 6. (a) Residuals after fitting for ν, $\dot{\nu}$, $\ddot{\nu}$, the Keplerian orbital parameters and jumps in ν and $\dot{\nu}$ at each periastron, giving an rms residual of 1.4 ms. (b) Post-fit residuals after adding a glitch at MJD 50691. The rms residual is 0.78 ms.

Figure 7. (a) Post-fit residuals for a fit of pulsar frequency and its first two derivatives, the Keplerian orbital parameters and jumps in the projected semimajor axis, x, at each periastron, giving an rms residual of 11 ms. (b) Post-fit residuals after the addition of a glitch at MJD 50691. The rms residual is now only 0.46 ms.

Wang et al. (2004)

11.8 脉冲星-主序星双星

Table 3. Four timing solutions for PSR B1259−63.

	No $\dot{\omega}$, $\dot{x}$	$\dot{\omega}$, $\dot{x}$	ν, $\dot{\nu}$ jumps	Orbital jumps
RA (J2000)	$13^{\rm h}02^{\rm m}47\overset{\rm s}{.}65(1)$	$13^{\rm h}02^{\rm m}47\overset{\rm s}{.}65(1)$	$13^{\rm h}02^{\rm m}47\overset{\rm s}{.}65(1)$	$13^{\rm h}02^{\rm m}47\overset{\rm s}{.}65(1)$
Dec. (J2000)	$-63°50'08\overset{''}{.}7(1)$	$-63°50'08\overset{''}{.}7(1)$	$-63°50'08\overset{''}{.}7(1)$	$-63°50'08\overset{''}{.}7(1)$
DM (pc cm^{-3})	146.8	146.8	146.8	146.8
ν (s^{-1})	20.93692453667(7)	20.9369245383(1)	20.93692435(4)	20.9369245339(9)
$\dot{\nu}$($\times 10^{-12}$s^{-2})	−0.9979077(6)	−0.9978663(7)	−0.9987(2)	−0.9979383(9)
$\ddot{\nu}$($\times 10^{-24}$s^{-3})	−2.11(2)	−1.96(2)	0.5(5)	−1.762(7)
Period epoch (MJD)	50357.00	50357.00	50357.00	50357.00
x (s)	1296.315(2)	1296.282(2)	1296.3264(4)	1296.272(5)
e	0.8698869(5)	0.8698832(6)	0.8698902(2)	0.8698872(9)
t_0 (MJD)	48124.3491(1)	48124.3494(2)	48124.34892(3)	48124.34911(9)
$P_{\rm b}$ (d)	1236.72404(3)	1236.72360(7)	1236.724259(7)	1236.72432(2)
ω (deg)	138.66588(7)	138.6644(1)	138.66624(6)	138.6659(1)
Glitch epoch (MJD)	50690.7	50690.7	50690.7	50690.7(7)
$\Delta\nu_{\rm g}$($\times$ 10^{-9} s^{-1})	67	67	67	67(1)
$\Delta\nu_{\rm d}$($\times$ 10^{-9} s^{-1})	22	22	22	22(1)
$\dot{\omega}$ (deg yr^{-1})	–	0.00020(1)	–	–
$\dot{x}$ ($\times$ 10^{-12})	–	127(5)	–	–
$\Delta\nu_{90}$($\times$ 10^{-9} s^{-1})	–	–	0(3)	–
$\Delta\dot{\nu}_{90}$($\times 10^{-15}$ s^{-2})	–	–	0.8(2)	–
$\Delta\nu_{94}$($\times$ 10^{-9} s^{-1})	–	–	15(3)	–
$\Delta\dot{\nu}_{94}$($\times 10^{-15}$ s^{-2})	–	–	0.19(5)	–
$\Delta\nu_{97}$($\times$ 10^{-9} s^{-1})	–	–	−10(3)	–
$\Delta\dot{\nu}_{97}$($\times 10^{-15}$ s^{-2})	–	–	−0.30(5)	–
$\Delta\nu_{00}$($\times$ 10^{-9} s^{-1})	–	–	−2(3)	–
$\Delta\dot{\nu}_{00}$($\times 10^{-15}$ s^{-2})	–	–	−0.33(5)	–
Δx_{90} (ms)	–	–	–	60.3(7)
Δx_{94} (ms)	–	–	–	−26.3(1)
Δx_{97} (ms)	–	–	–	2.8(3)
Δx_{00} (ms)	–	–	–	4.2(4)
No. TOAs	1031	1031	1031	1031
rms residual (ms)	4.3	4.7	0.78	0.46

总　结

毫秒脉冲星是区别于正常脉冲星的一类特殊群体。尽管有关它们的观测现象是丰富的，但一个非常基本的问题还一直没有回答:

它们真的是通过再加速形成的吗?