AGA0293 Astrofísica Estelar
Profa. Jane Gregorio-Hetem

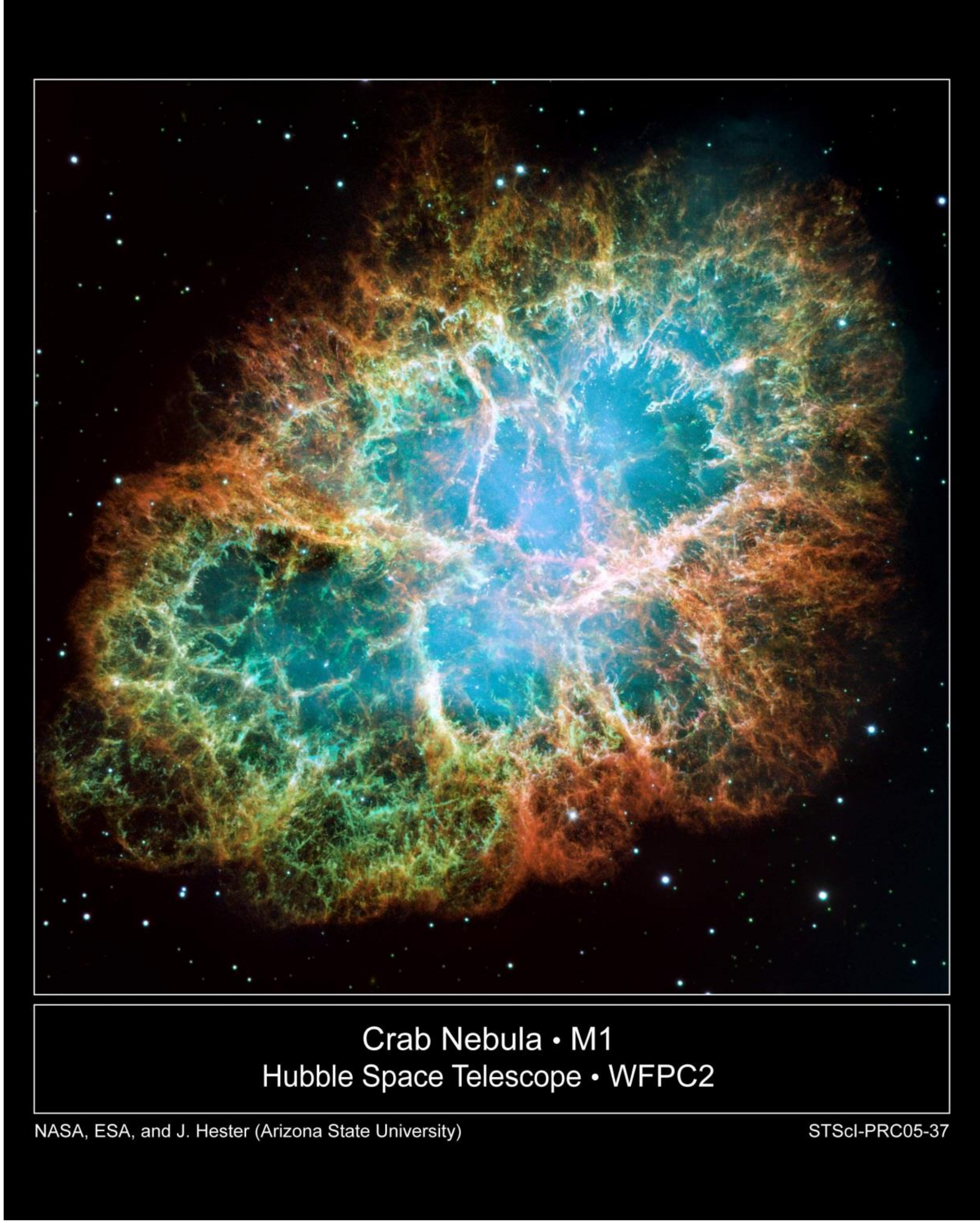
Capítulo 15
Evolução de Estrelas Massivas

15.1 Evolução das estrelas massivas após a Sequência Principal
15.2 Classificação de Supernovas
15.3 Supernovas de colapso de *core*
15.4 *Gamma ray bursts* 15.5 Raios cósmicos

Explosão de supernova

Camadas externas ejetadas violentamente

- SN tipo II, Ib, Ic: colapso de *core* de estrelas muito massivas ⇨ estrela de neutrons ou buraco negro ($M > 25 M_\odot$)
- SN tipo Ia: sistemas binários - anã branca recebe matéria da companheira ⇨ se desintegra após explosão (modelos ainda em discussão)



15.2 Classificação de supernovas

HISTÓRICO

Supernova 1006

V ~ -7,5 (a mais brilhante já observada)

d = 2,2 kpc

Coordenadas:

A.R.= 15 02 22.1 Dec =-42 05 49

صورة كوكب من الكواكب ، كالذى ظهر فى سنة سبع وتسعين وثلاث مائة للهجرة ،
فبقى قريبا من ثلاثة أشهر يلطف و يلطف حتى اضمحل ، وكان فى ابتدائه إلى السواد
والخضرة ، ثم جعل كل وقت يرمى بالشرر ويزداد بياضا و يلطف حتى اضمحل . وقد
يكون على صورة لحية ، أو صورة حيوان له قرون ، وعلى سائر الصور ؛ وإنما يكون ذلك
إذا كانت هناك مادة كثيفة واقفة ، فالطف أجزاؤها يسيرا يسيرا وتحلل عنه متصعدة
كزوائد شعرية أو قرنية . ومنها المسماة أعتا كأن تشريرها تشعير . وكل ما ثبت منها

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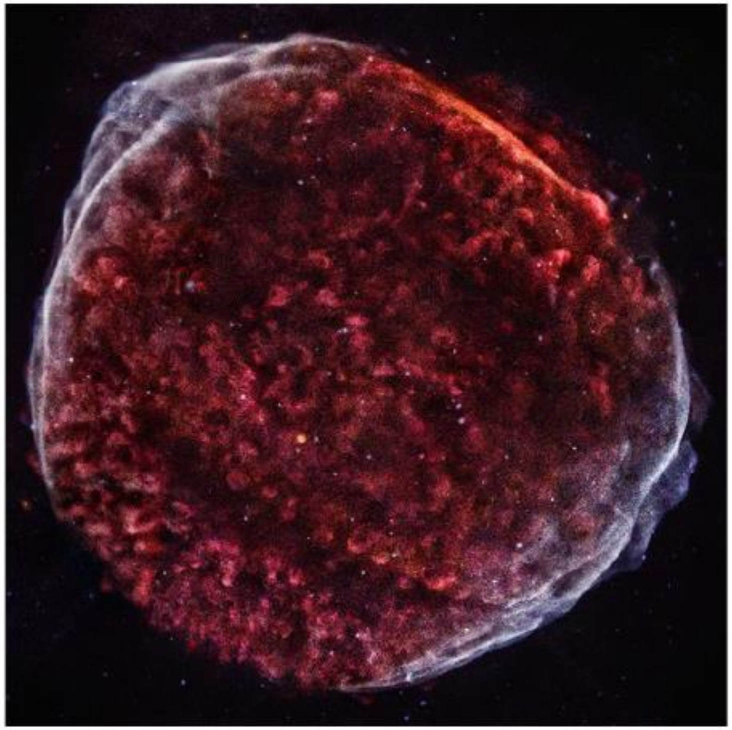
(١) بالعدد : وبالعدد د ، سا || ق : ساقطة من ب ، ط (٢) كالموجودة : كالموجود
د ، ط ، م (٣) ويخلفها غيرها : ويخلفه غيره ب ، د ، سا ، ط || موضعها : موضعه ب ، د ، سا ، ط .
(٥) فى حقيقة : وحقيقة سا (٧) مقامه : مكانه د ، سا || يشتمل : ساقطة من د .
(٨) وخفيفة : خفيفة سا (٩) وخلصت : وحصلت سا . (١٠) وذات : ذات سا

Arabic text from the report of SN 1006 of Ibn Sina in al-Shifa from the Arabic edition by Madkur et al. (1965)

X-rays, Chandra @NASA



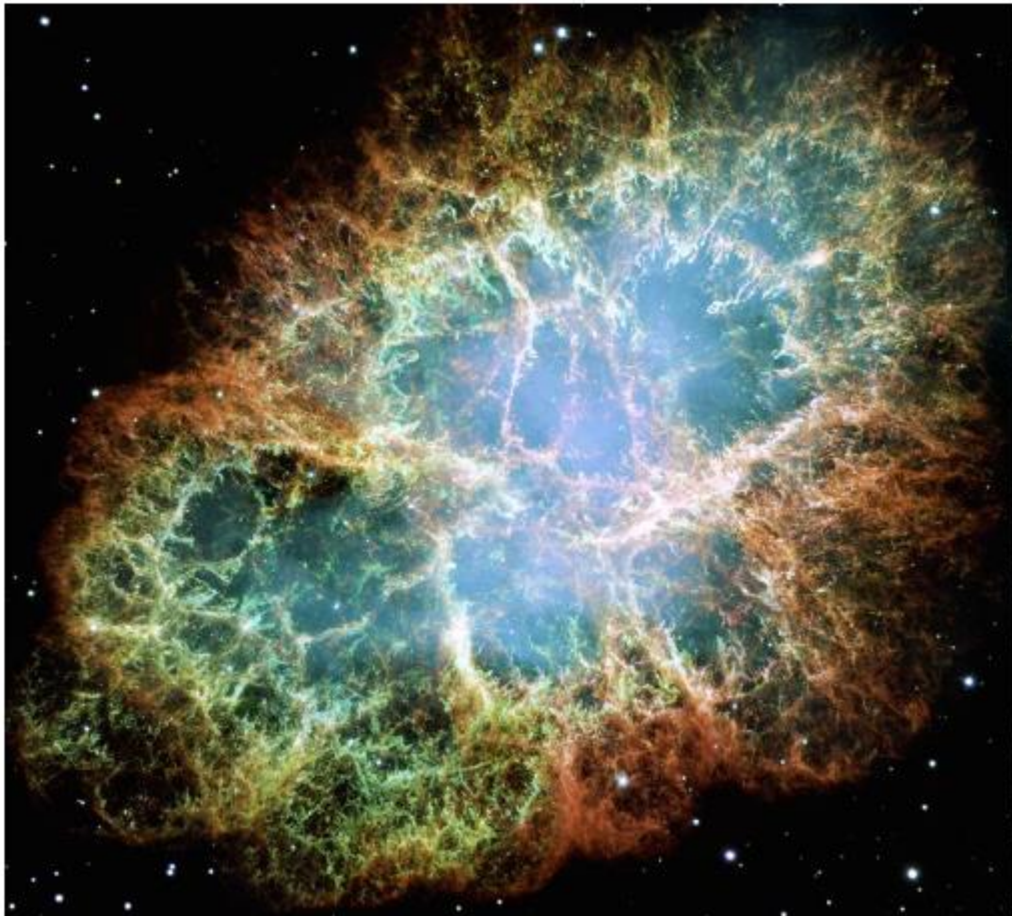
Text 2. Ibn al-Athir: Events of A.H. 396.

وفيها مستهل شعبان طلع كوكب كبير تشبه الزهرة عن
يسرة قبله العراق له شعاع على ارض كشعاع القمر وبقى
الى منتصف ذى القعدة وغاب .

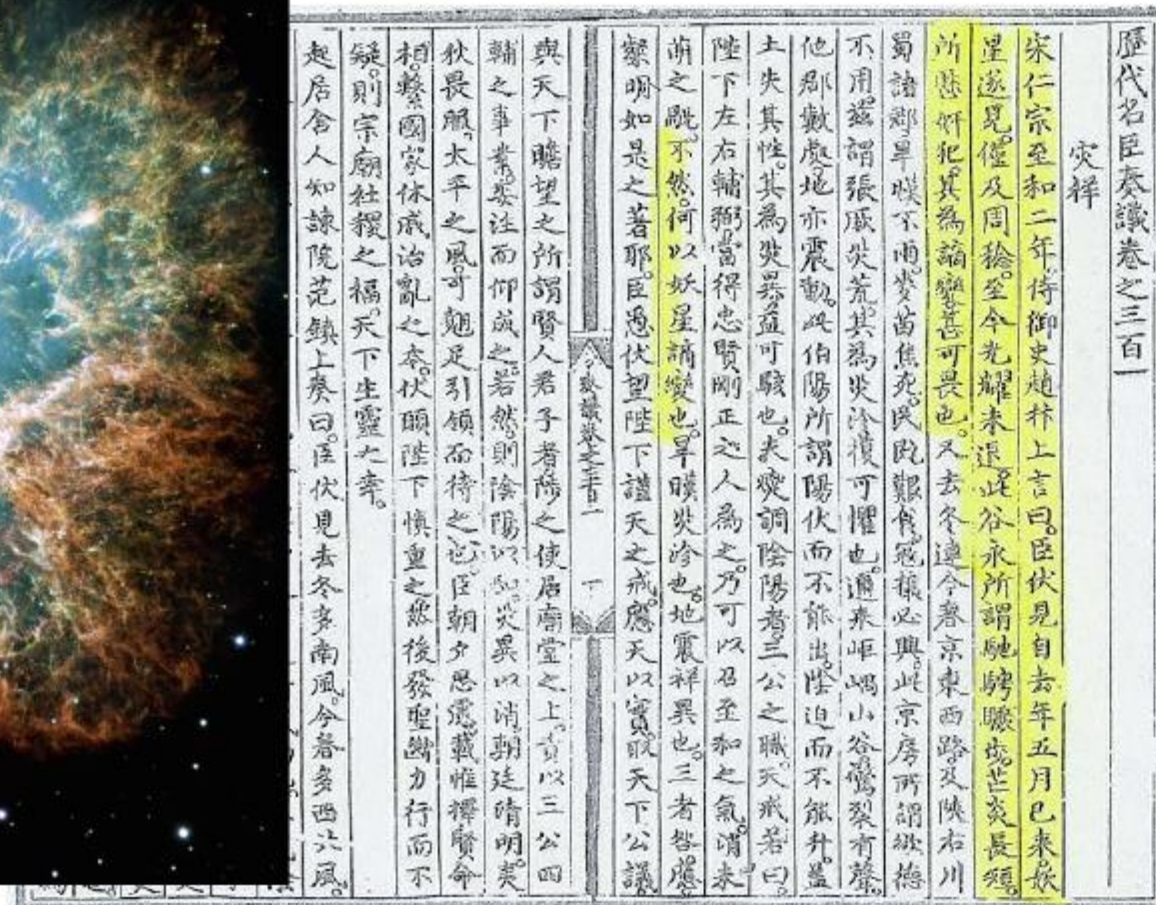
Goldstein (1965, ApJ 70, 105)

Supernova 1054

V ~ -6, d ~ 2 kpc



Crab nebula
© HST



災祥

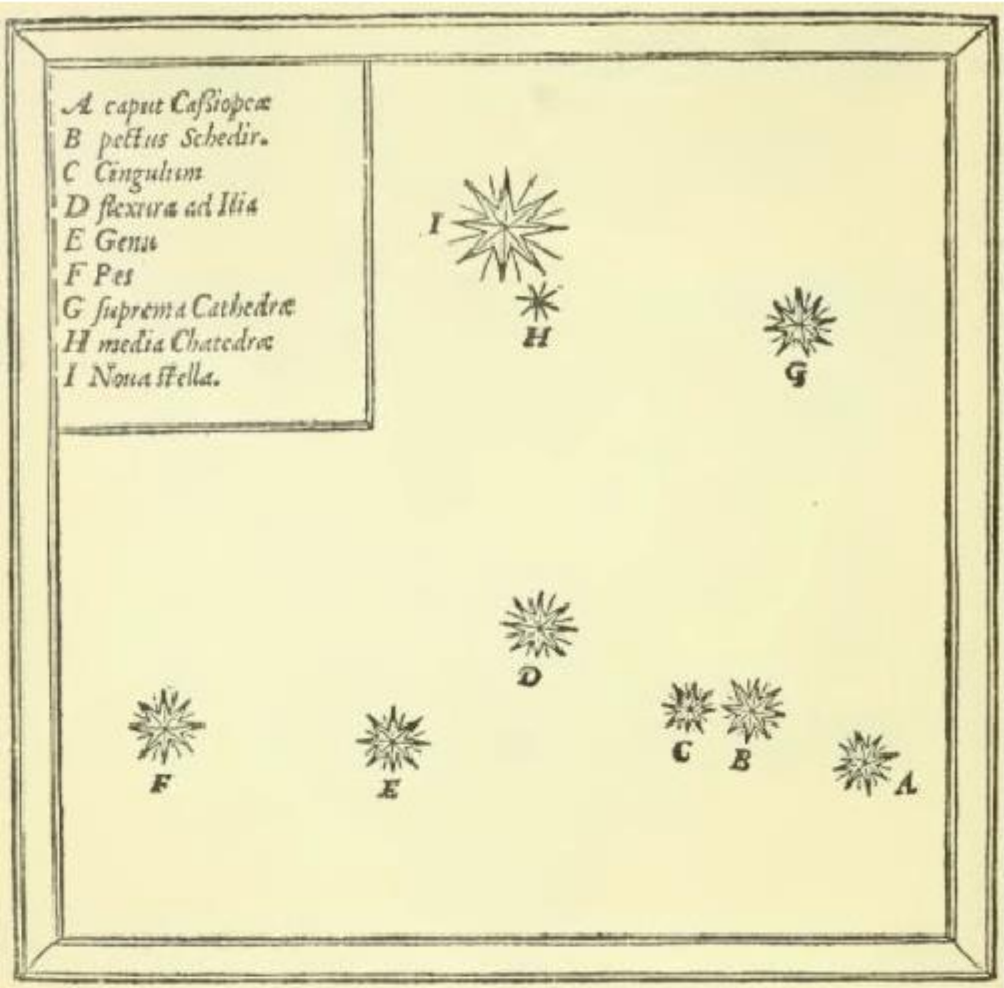
宋仁宗至和二年侍御史趙抃上言曰臣伏見自去年五月已來妖
星遂見僅及周稔至今光耀未退此谷永所謂馳騁驟步芒炎長短
所懸犯其為譴變甚可畏也又去冬違令春京東西路及陜右川
蜀諸郡旱暵不雨麥苗焦死民既艱食寇攘必興此京房所謂繇搖
不用蠻謂張厥災荒其為災沴擭可懼也邇來岷峨山谷震裂有聲
他郡數處地亦震動此伯陽所謂陽伏而不能出陰迫而不能升蓋
土失其性其為災異益可駭也夫燮調陰陽者三公之職天戒若曰
陛下左右輔弼當得忠賢剛正之人為之乃可以召至和之氣消未
萌之亂不然何以妖星譴變也旱暵災沴也地震祥異也三者皆應
響明如是之著耶臣愚伏望陛下謹天之戒應天以實取天下公議

與天下瞻望之所謂賢人君子者俾之使居廟堂之上責以三公四
輔之事業委注而仰成之若然則陰陽以和災異以消朝廷清明矣
狄長亂太平之風可翹足引領而待之也臣朝夕思慮載惟擇賢命
相整國家休戚治亂之本伏願陛下慎重之然後發聖斷力行而不
疑則宗廟社稷之福天下生靈之幸
起居舍人知諫院范鎮上奏曰臣伏見去冬多南風今春多西北風

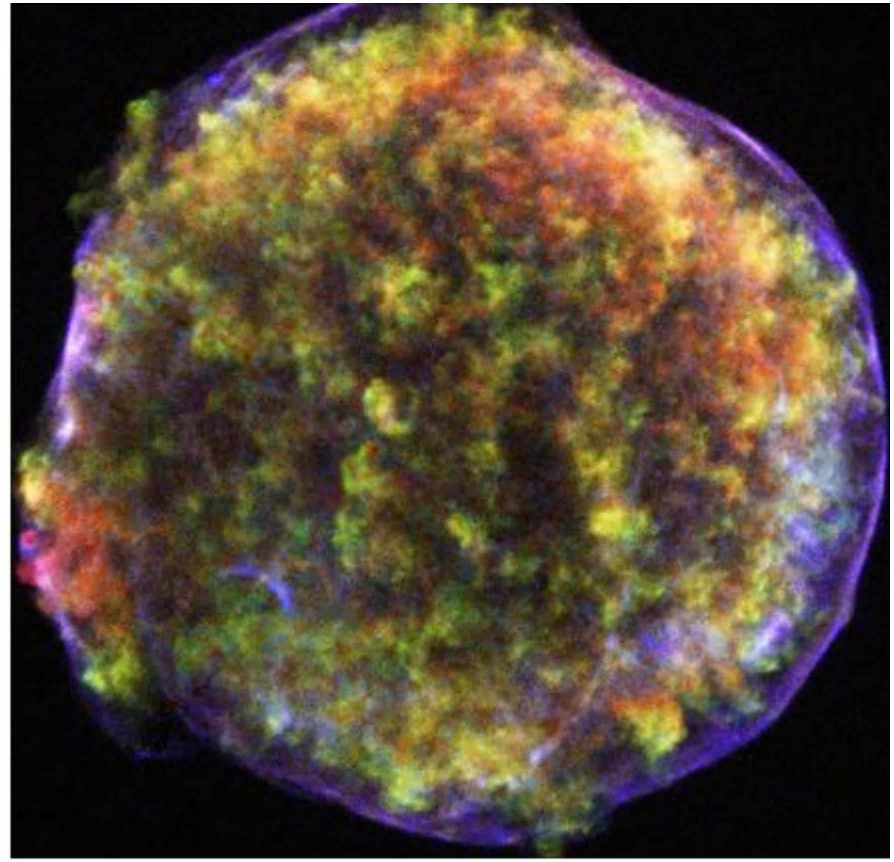
The guest star reported by Chinese astronomers in 1054 is identified as SN 1054. The highlighted passages refer to the supernova.

Supernova 1572

V ~ -4, d ~ 2,7 kpc

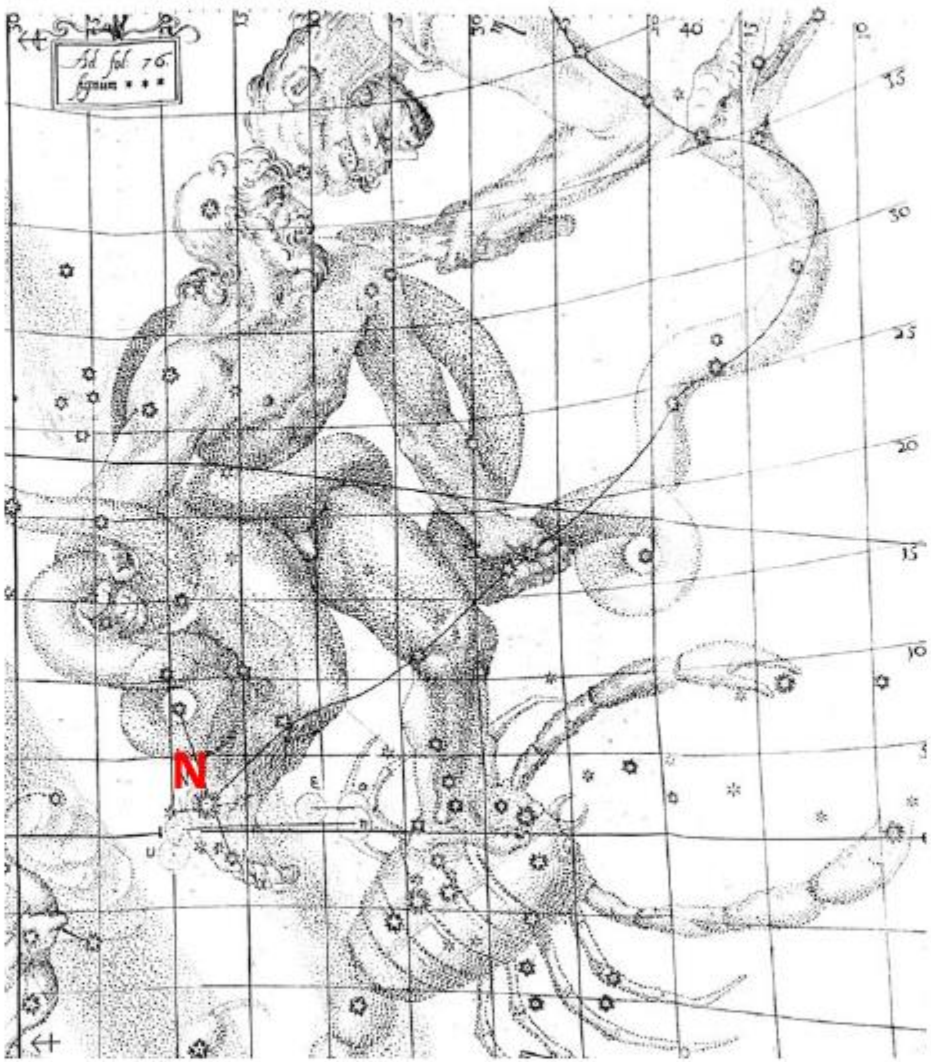


Tycho's notes on SN 1572

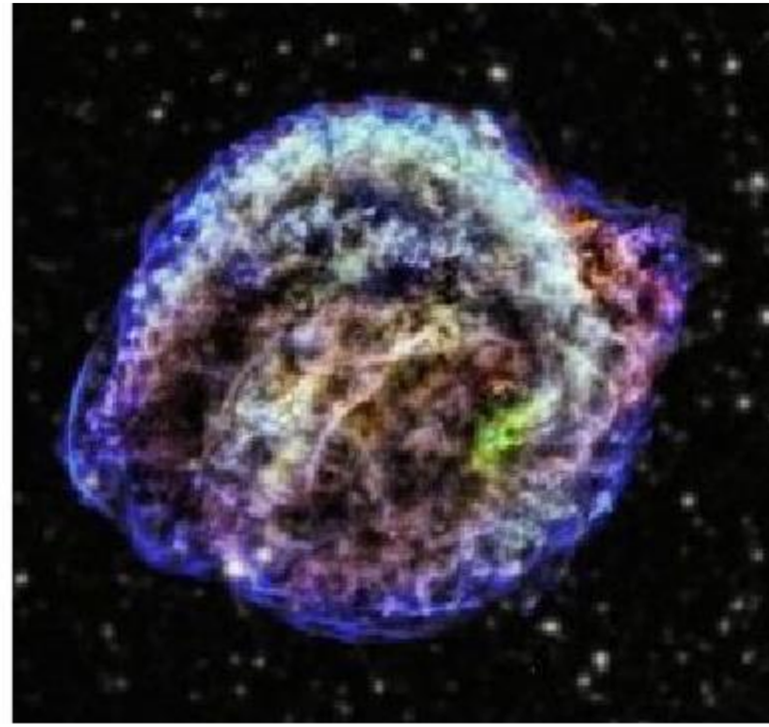


Tycho's Supernova Remnant. Chandra's image of the supernova remnant shows an expanding bubble of multimillion degree debris (green and red) inside a more rapidly moving shell of extremely high energy electrons (filamentary blue).

Supernova 1604,
V ~ -2,4, d ~ 6 kpc



Kepler's original drawing depicting the location of the stella nova (N)



Remnant of Kepler's supernova, the famous explosion that was discovered by Johannes Kepler in 1604. The red, green and blue colors show low, intermediate and high energy X-rays observed with NASA's Chandra X-ray Observatory, and the star field is from the Digitized Sky Survey.

Supernova 1987A,

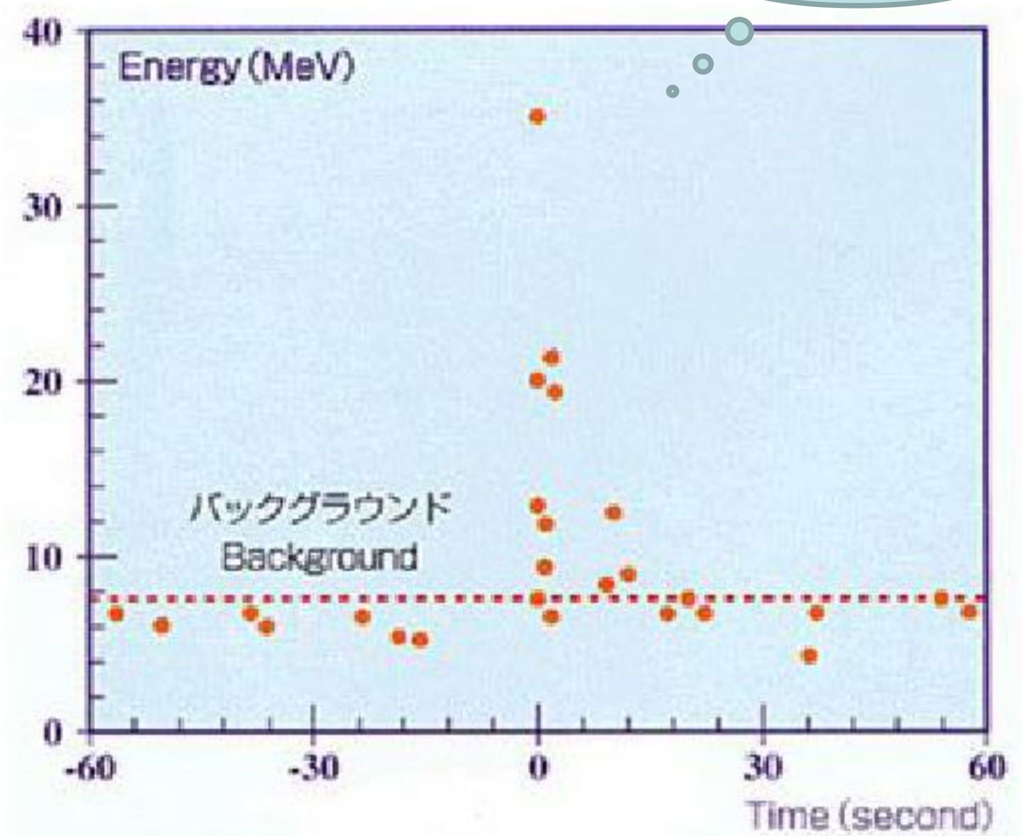
V ~ 2,9; d ~ 51,4 kpc

The progenitor star was identified as Sanduleak −69° 202, a blue supergiant, B3I (V = 12)

T = 16 000 K
$L = 1{,}1 \times 10^5\ L_{Sol}$

Supernova 1987A after exploding & an image before the explosion. (c) David Malin / AAO

Fluxo medido na Terra
$1{,}3 \times 10^{14}$ neutrinos/m^2



Kamiokande (large water Cherenkov detector) detected 11 events of neutrinos from the 1987A supernova.

http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/supernova-e.html

8 events were also detected in the USA.

Both neutrino detections occurred hours before the optical detection → neutrinos must have travelled close to *c*.

Tipos de Supernovas

- Eventos muito raros: 1 a cada 100 anos.
- Classificação com base nas curvas de luz e nos espectros → depende da estrela progenitora e dos mecanismos.
- **Tipo II**: espectro com fortes linhas de H
- **Tipo I**: espectro sem linhas de H

    Ib: presença de fortes linhas do He

    Ic: ausência de fortes linhas do He

    Ia: forte linha do Si II em 615nm

Colapso de *core* de estrela massiva

Sistema binário

Tipo Ia: sem H
com SiII

Tipo II:
com H

Tipo Ic:
sem H
sem He

Tipo Ib:
sem H
com He

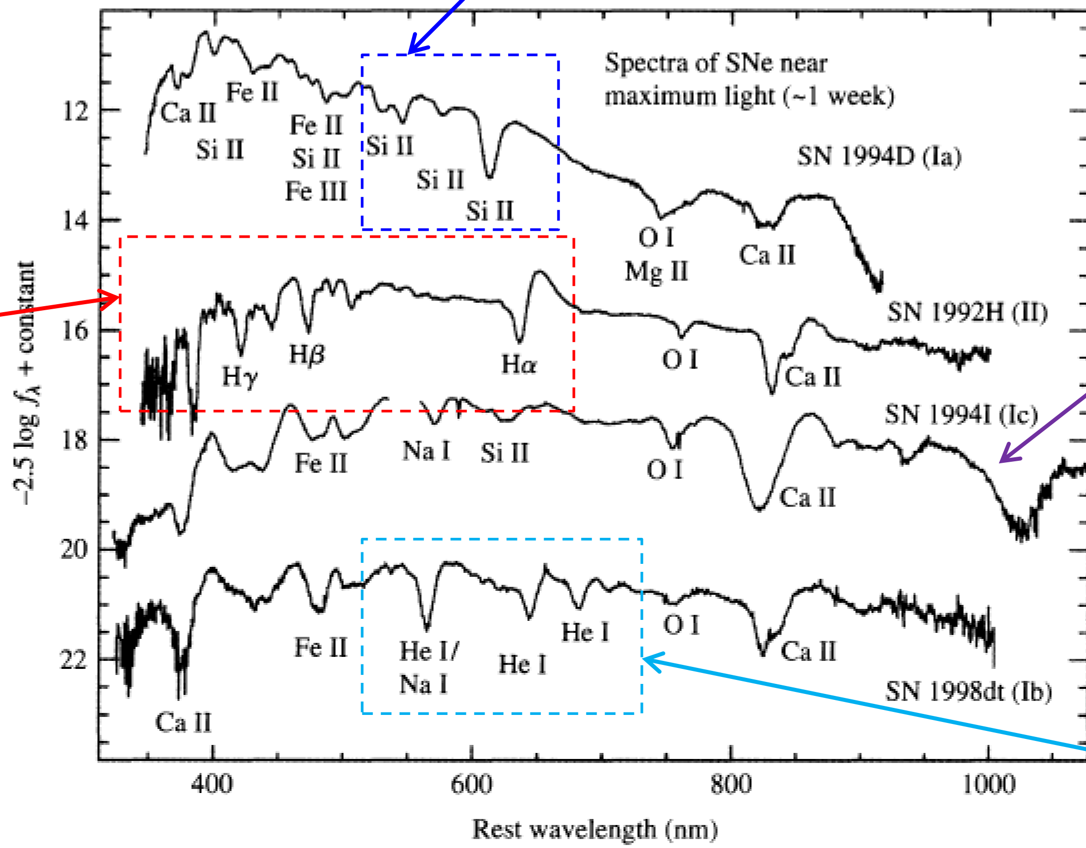


FIGURE 15.6 Representative spectra of the four types of supernovae; Type Ia, Ib, Ic, and II. Note that although SN 1994I (Type Ic) does exhibit a weak Si II absorption line, it is much less prominent than the Si lines in a Type Ia. Brightness is in arbitrary flux units. (Courtesy of Thomas Matheson, National Optical Astronomy Observatory.)

SN Tipo I (Tycho (SN1572); Kepler (SN1604))

Curva de luz: O máximo de brilho para Tipo Ia é M_B = -18,4 mag.

Nos tipos Ib e Ic → pico no brilho é 1,5 a 2 mag mais fraco.

Decaimento de ~0,065 mag/dia em 20 dias. Depois de 50 dias a diminuição de brilho é menor e se torna ~constante.

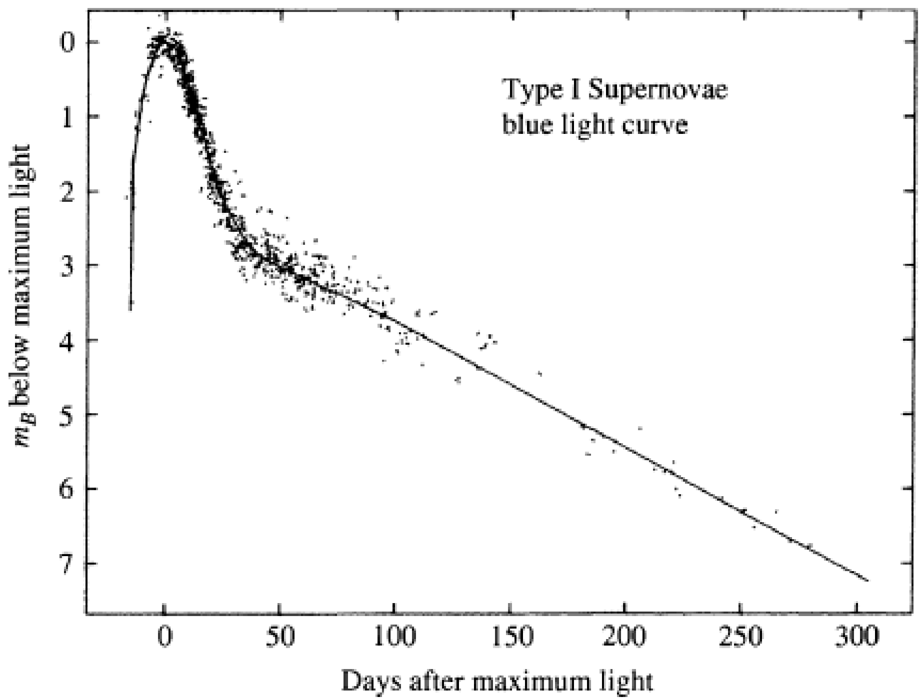


FIGURE 15.7 Composite light curve for Type I supernovae at blue wavelengths. All magnitudes are relative to m_B at maximum. (Figure adapted from Doggett and Branch, *Astron. J.*, *90*, 2303, 1985.)

SN Tipo II (Crab (SN1054) e SN1987A)

- Espectro mostra linhas de H e metais mais pesados;
- Perfil PCygni (Cap. 12.3) comum em várias linhas → rápida expansão

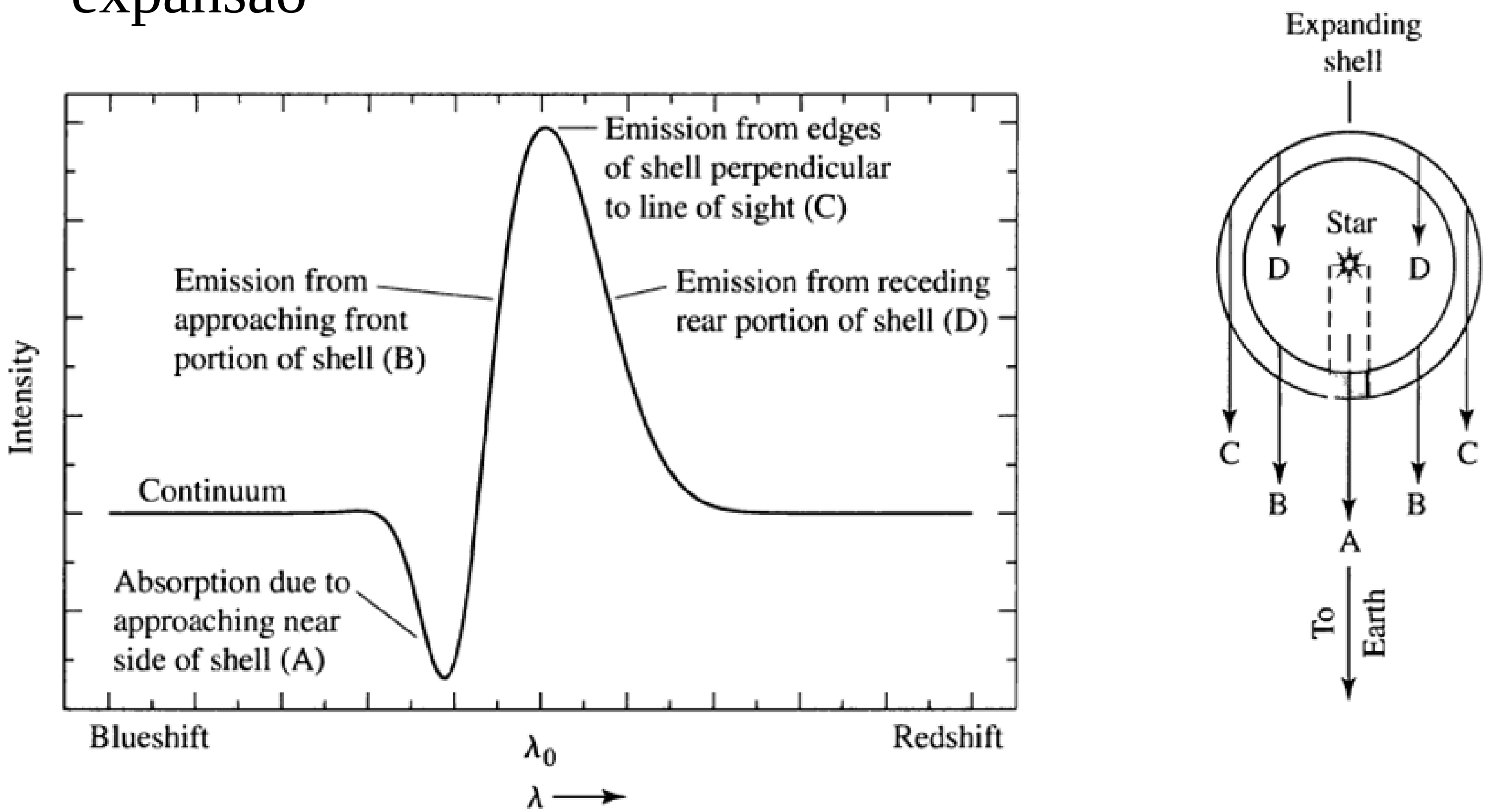
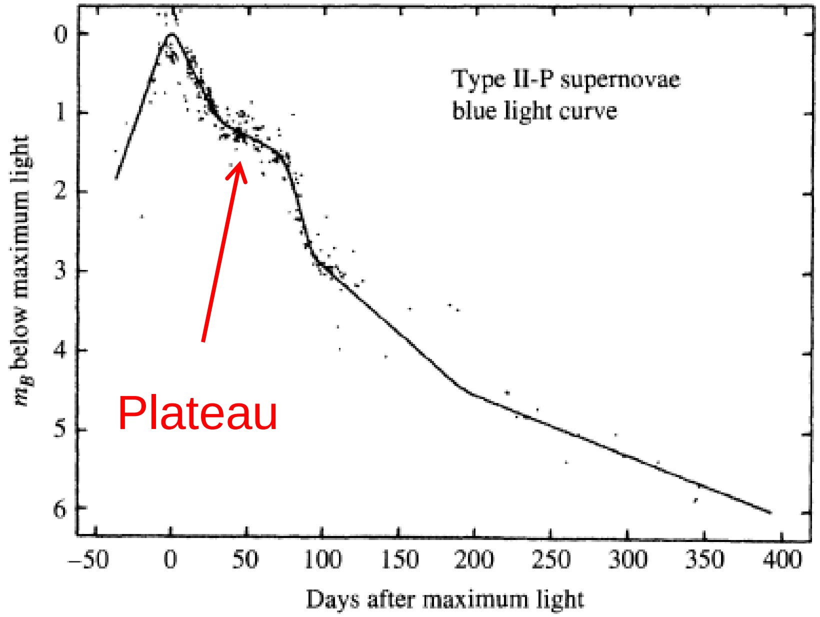


FIGURE 12.17 (a) A spectral line exhibiting a P Cygni profile is characterized by a broad emission peak with a superimposed blueshifted absorption trough. (b) A P Cygni profile is produced by an

Curva de luz:
Rápido crescimento no brilho, chegando a um máximo com cerca de 1,5 mag menor que no caso do Tipo Ia.
Decaimento do brilho ocorre em 6 a 8 mag em 1 ano.
Tipo II-P (*plateau*): depois do máximo ocorre um plateau temporário (30 a 80 dias). Ocorrem com frequência 10 vezes maior que as de Tipo II-L.
Tipo II – L (linear): sem evidência de *plateau*.



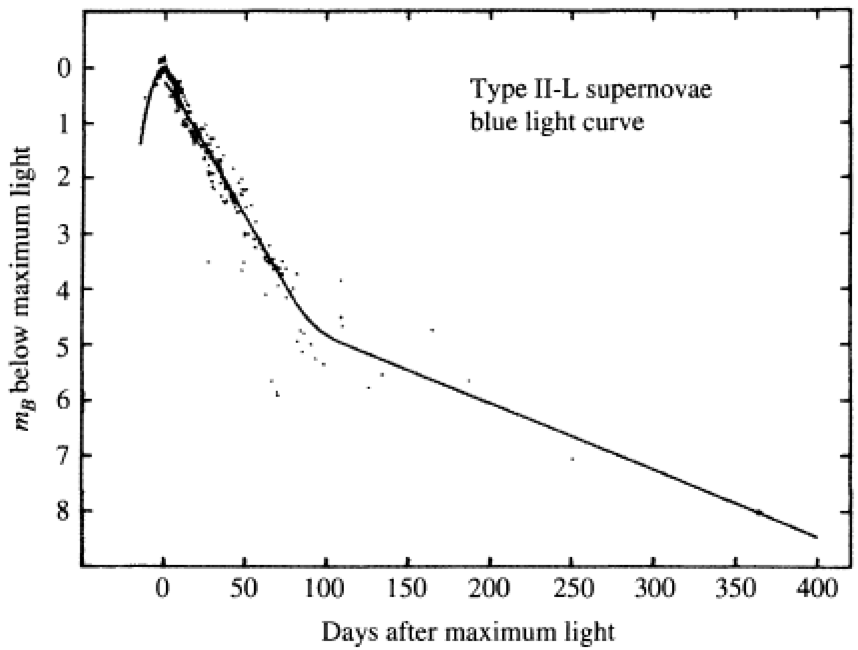


FIGURE 15.8 The characteristic shapes of Type II-P and Type II-L light curves. These are composite light curves, based on the observations of many supernovae. (Figures adapted from Doggett and Branch, *Astron. J.*, *90*, 2303, 1985.)

Resumo dos 3 tipos de Supernovas

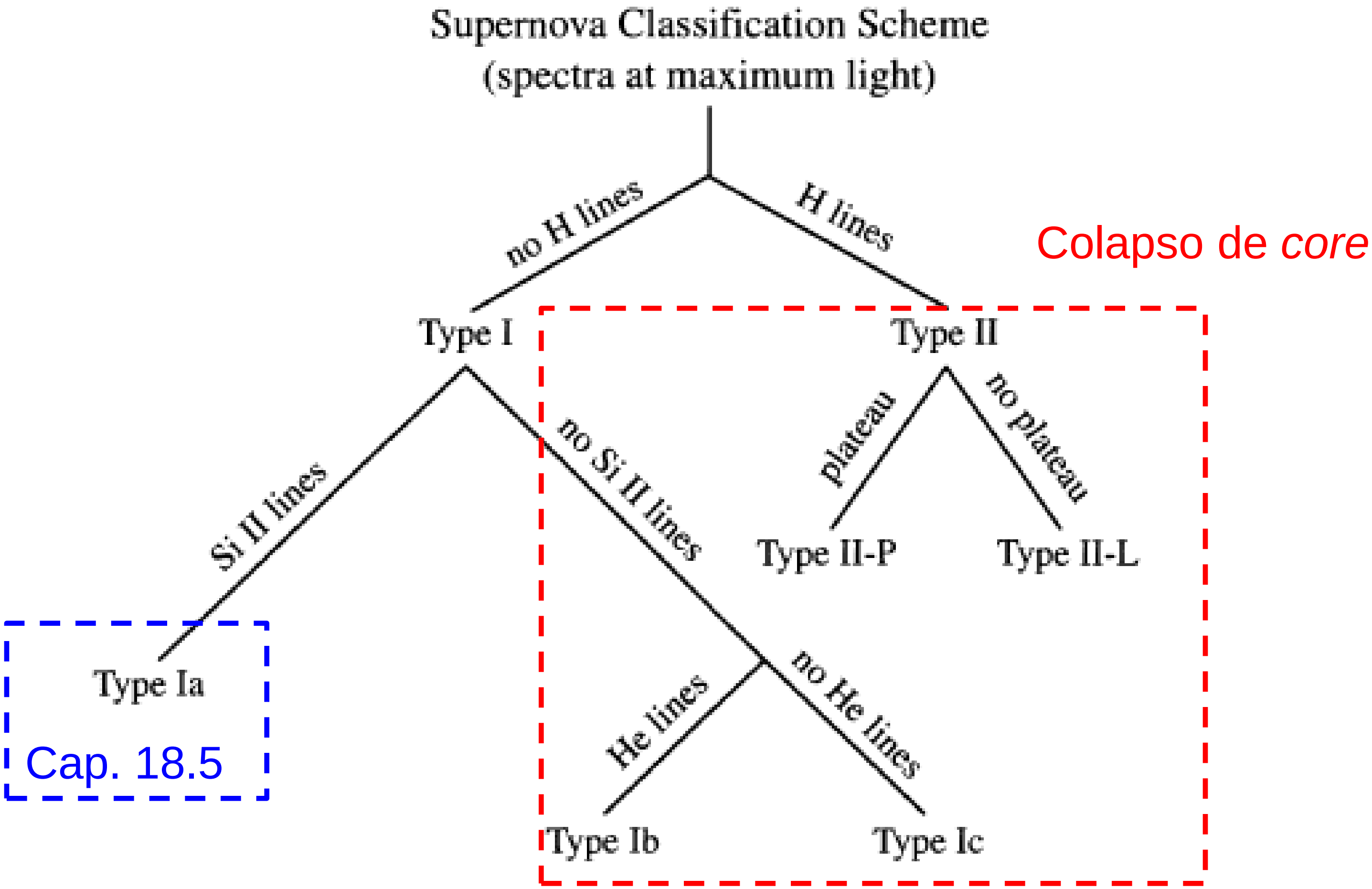
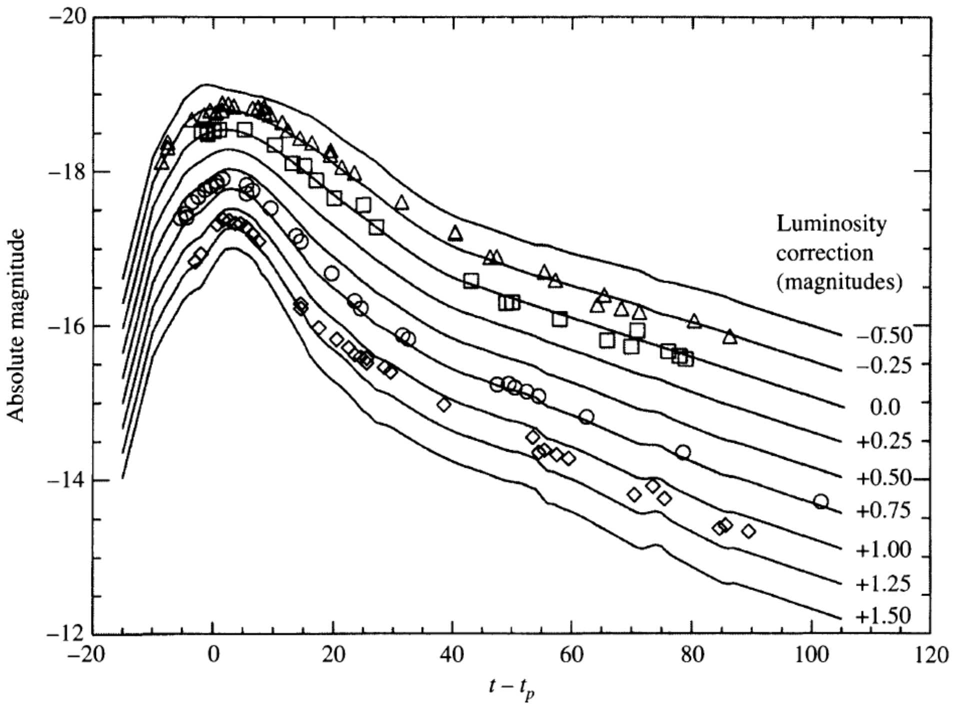


FIGURE 15.9 The classification of supernovae based on their spectra at maximum light and the existence or absence of a plateau in the Type II light curve.

relationship exists between the peak brightness and the rate of decline in the light curve (the brightest Type Ia's decline the slowest), making it possible to accurately determine the maximum luminosity of an individual Type Ia by measuring the rate of decline. Knowing the luminosity (or absolute magnitude), we can compute the distance to the supernova.

astronomers can probe the structure of the universe to great distances. In fact, Type Ia supernovae played a crucial role in demonstrating that the expansion of the universe is actually accelerating today, 13.7 billion years after the Big Bang, and that nearly three-fourths of the universe consists of **dark energy**.



SN Ia
("*standardizable candles*")

são cruciais nas medidas de distância mais remotas

FIGURE 18.21 The rate of decline in the light curve of a Type Ia supernova is inversely correlated with the maximum brightness of the light curve. (Figure adapted from Riess, Press, and Kirshner, *Ap. J.*, *438*, L17, 1995.)

15.3 Colapso de *core* de estrelas massivas

- Estrelas com $M < 8\ M_\odot$ → Nebulosa Planetária
- Estrelas com $M > 8\ M_\odot$ → SN Tipo II, Ib, Ic

Tipo II: Liberação de 10^{46} J de energia:

1%: energia cinética do material ejetado

0,01%: liberação de fótons

~99%: neutrinos

Example 15.3.1. To illustrate how much energy is involved in a Type II event, consider the equivalent amount of rest mass, and how much iron could ultimately be produced by releasing that much nuclear binding energy.

Exemplo 15.3.1

From $E = mc^2$, the energy released by a Type II supernova corresponds to a rest mass of

$$m = E/c^2 = 10^{46}\ \mathrm{J}/c^2 = 1 \times 10^{29}\ \mathrm{kg} = 0.06\ \mathrm{M}_\odot.$$

The binding energy of an iron-56 nucleus ($^{56}_{26}\mathrm{Fe}$), the most stable of all nuclei, is 492.26 MeV, and the mass of the nucleus is 55.934939 u (recall Fig. 10.9). In order to release 10^{46} J of energy through the formation of iron nuclei from protons and neutrons, it would be necessary to form

$$N = \left(\frac{1 \times 10^{46}\ \mathrm{J}}{492.26\ \mathrm{MeV/nucleus}}\right)\left(\frac{1\ \mathrm{MeV}}{1.6 \times 10^{-13}\ \mathrm{J}}\right) = 1.3 \times 10^{56}\ \text{nuclei},$$

corresponding to a mass of iron of

$$m = N(55.93\ \mathrm{u})(1.66 \times 10^{-27}\ \mathrm{kg/u}) = 1.2 \times 10^{31}\ \mathrm{kg} = 5.9\ \mathrm{M}_\odot.$$

Of course this would require that 5.9 $\mathrm{M}_\odot$ of iron be produced all at once in an explosive event if this is the source of the energy for a Type II supernova! On the other hand, if this much iron were broken down to the original protons and neutrons, the equivalent amount of energy would need to be absorbed.

Mecanismos do colapso de *core*

- Queima de He adiciona continuamente C-O no *core*.
- O *core* está em continua contração → eventualmente inicia-se a queima de C, gerando vários subprodutos ($_8O^{16}$, $_{10}Ne^{20}$,..., $_{12}Mg^{24}$)
- Sequência de reações nucleares → cada uma em camadas da estrela, em equilíbrio.
- Nas temperaturas ~3 ×10^9 K → queima de Si em núcleos próximos ao Fe

$$^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} \rightleftharpoons {}^{32}_{16}\mathrm{S} + \gamma$$

$$^{32}_{16}\mathrm{S} + {}^{4}_{2}\mathrm{He} \rightleftharpoons {}^{36}_{18}\mathrm{Ar} + \gamma$$

$$\vdots$$

$$^{52}_{24}\mathrm{Cr} + {}^{4}_{2}\mathrm{He} \rightleftharpoons {}^{56}_{28}\mathrm{Ni} + \gamma.$$

Esquema da estrutura interna de uma estrela massiva que evoluiu até formar um *core* com queima de Si

Para 20 $M_\odot$

H: 10^7 anos

He: 10^6 anos

C: 300 anos

O: 200 dias

Si: 2 dias

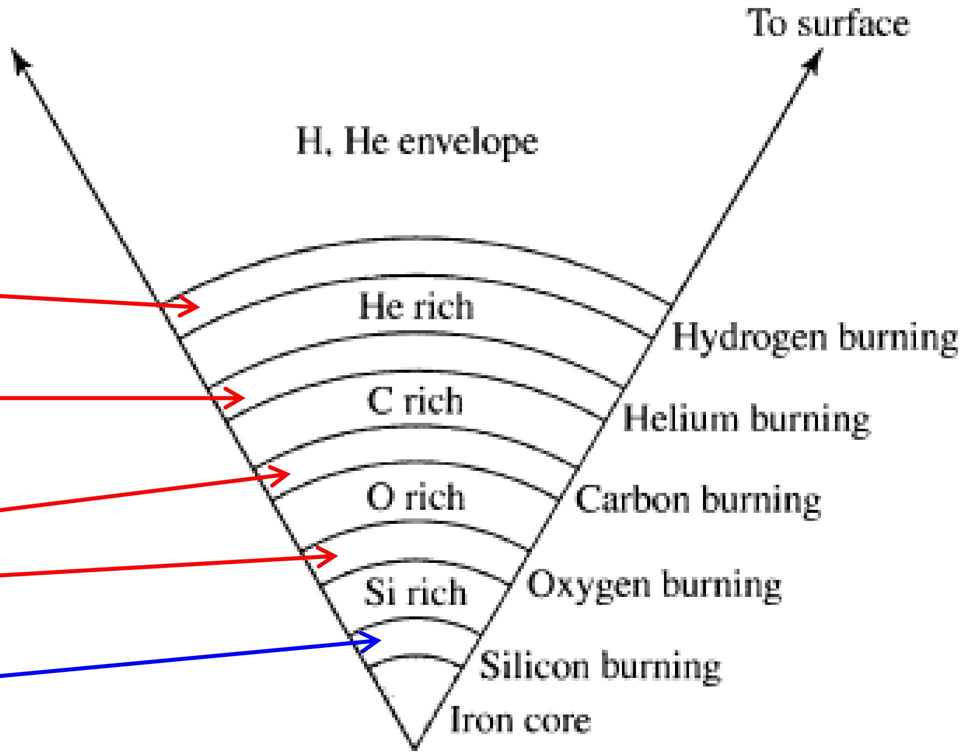
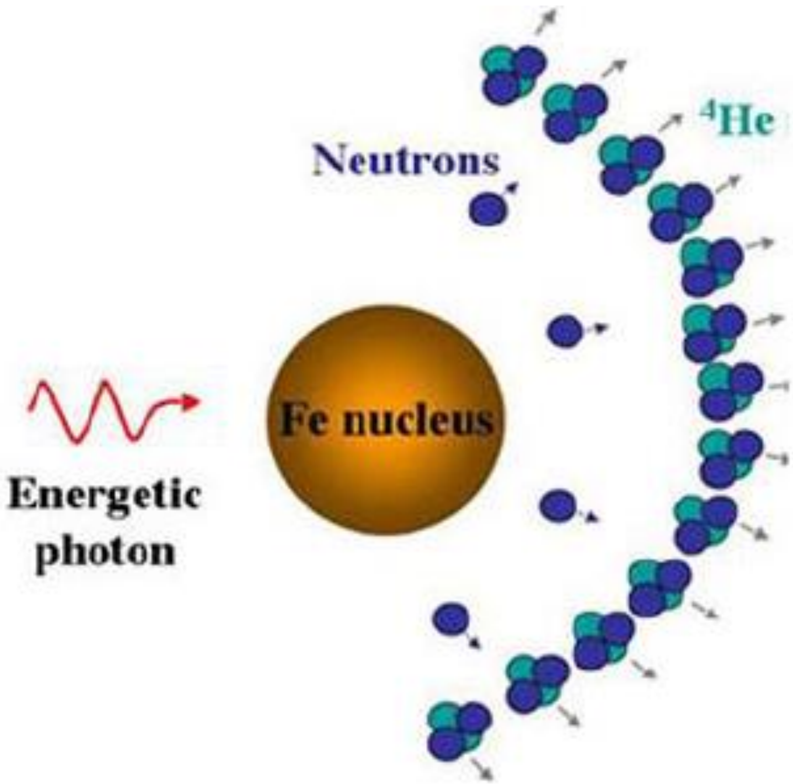


FIGURE 15.10 The onion-like interior of a massive star that has evolved through core silicon burning. Inert regions of processed material are sandwiched between the nuclear burning shells. The inert regions exist because the temperature and density are not sufficient to cause nuclear reactions to occur with that composition. (This drawing is not to scale.)



Temperaturas muito altas no núcleo → fotodesintegração.

$$^{56}_{26}\mathrm{Fe} + \gamma \rightarrow 13\,^{4}_{2}\mathrm{He} + 4n$$

$$^{4}_{2}\mathrm{He} + \gamma \rightarrow 2p^{+} + 2n.$$

Para estrela de 10 M_{Sol} → núcleo de ferro ~ 1,3 M_{Sol}
Para estrela de 50 M_{Sol} → núcleo de ferro ~ 2,5 M_{Sol}

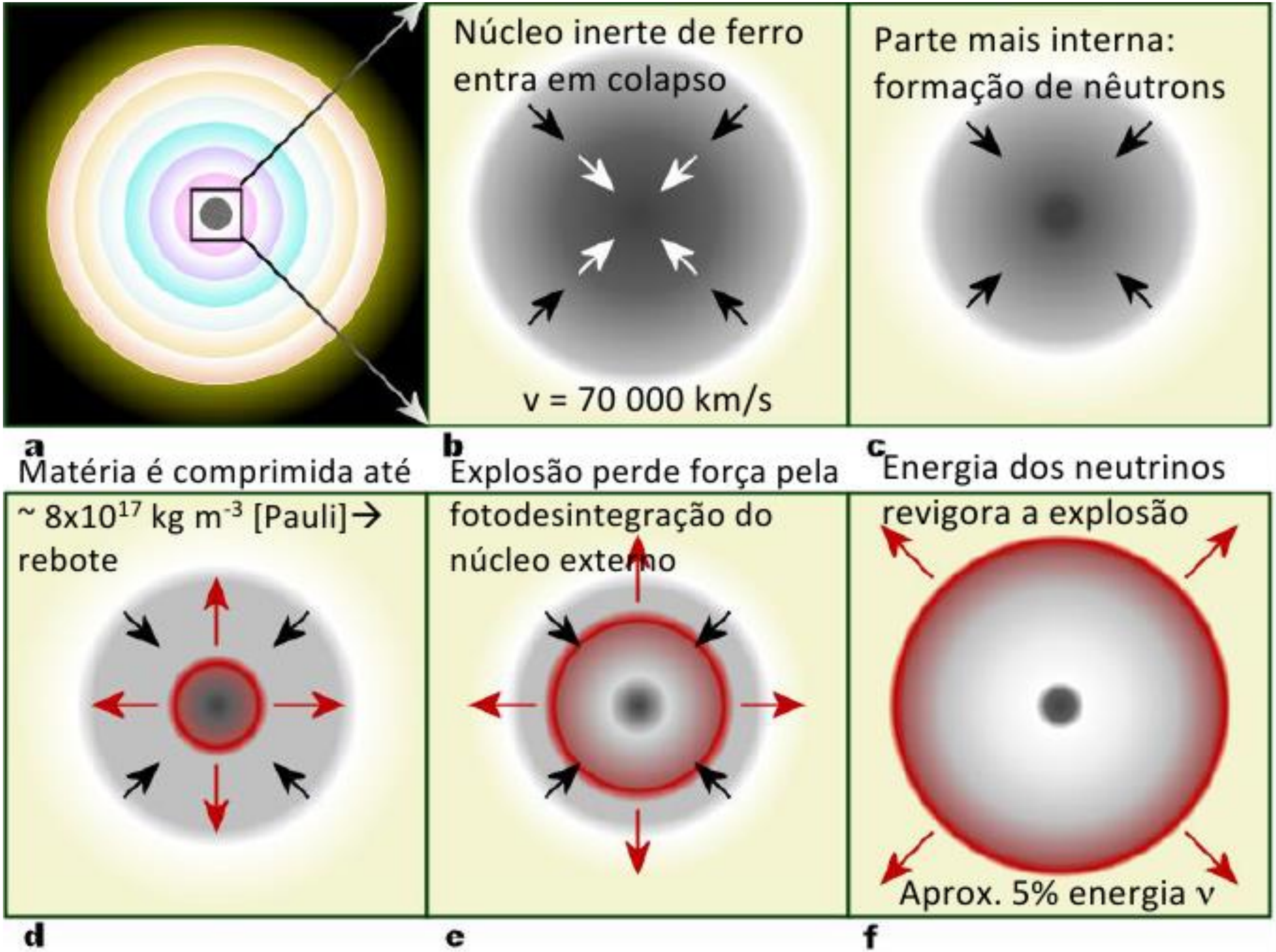
Condições extremas no núcleo inerte de ferro.
Para estrela de 15 M_{Sol}:
$T \sim 8 \times 10^9$ K
$\rho \sim 10^{13}$ kg m^{-3}

Elétrons livres são capturados pelos núcleos que foram produzidos na fotodesintegração. Por exemplo:

$$p^+ + e^- \rightarrow n + \nu_e$$

Muita energia escapa da estrela em forma de neutrinos.
Para estrela de 20 M_{Sol}: $L_{fótons} = 4 \times 10^{31}$ W, $L_\nu = 3 \times 10^{38}$ W

Núcleo da estrela fica sem suporte pois fótons são usados para fotodesintegração. Também, pressão de degenerescência de *e*- diminui devido à sua captura.


Núcleo inerte de ferro entra em colapso
v = 70 000 km/s
Parte mais interna: formação de nêutrons
a
b
c
Matéria é comprimida até ~ 8x10^17 kg m^-3 [Pauli]→ rebote
Explosão perde força pela fotodesintegração do núcleo externo
Energia dos neutrinos revigora a explosão
Aprox. 5% energia ν
d
e
f

Example 15.3.2. If a mass with the radius of Earth ($R_\oplus$) collapses to a radius of only 50 km, a tremendous amount of gravitational potential energy would be released. Can this energy release be responsible for the energy of a core-collapse supernova?

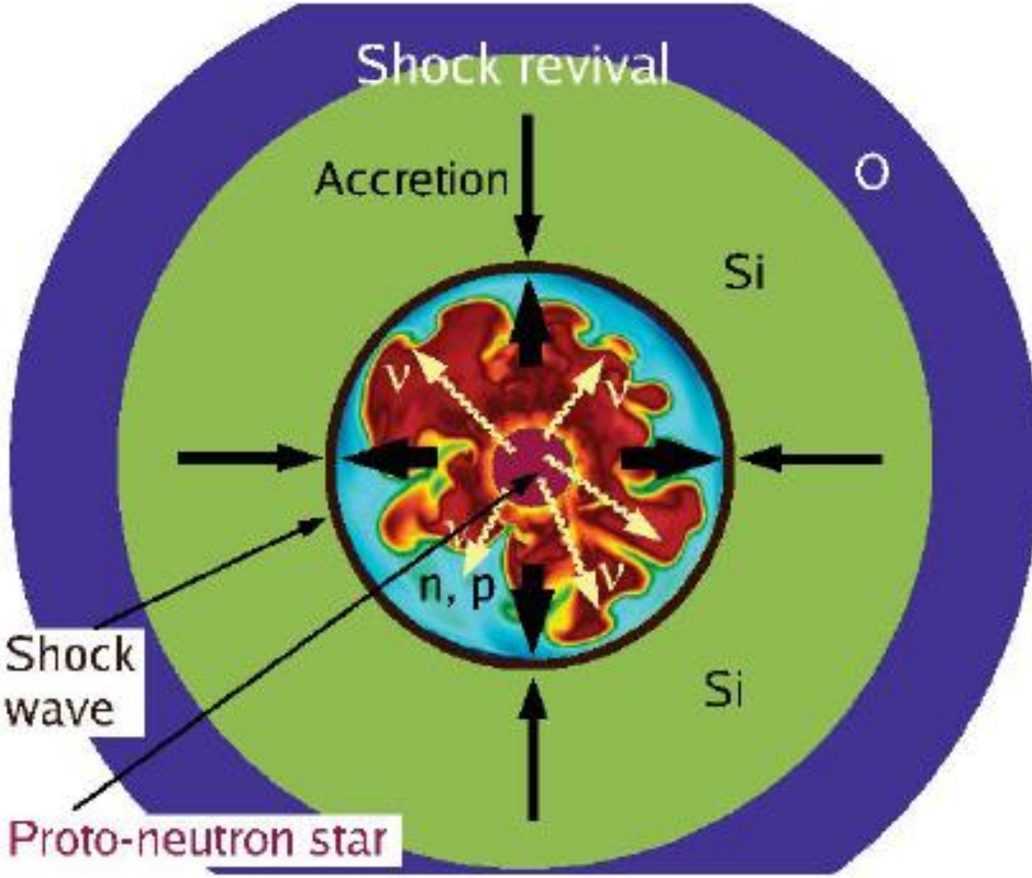
Assume for simplicity that we can use Newtonian physics to estimate the amount of energy released during the collapse. From the virial theorem (see Eq. 10.23), the potential energy of a spherically symmetric star of constant density is

$$U = -\frac{3}{10}\frac{GM^2}{R}.$$

Equating the energy of a Type II supernova, $E_{\rm II} = 10^{46}$ J, to the gravitational energy released during the collapse, and given that $R_f = 50$ km $\ll R_\oplus$, the amount of mass required to produce the supernova would be

$$M \simeq \sqrt{\frac{10}{3}\frac{E_{\rm II}R_f}{G}} \simeq 5 \times 10^{30}\ \text{kg} \simeq 2.5\ \text{M}_\odot.$$

This value is characteristic of the core masses mentioned earlier.



Energia cinética total do material em expansão ~ 10^{44} J (~1% da energia liberada por neutrinos).

Quando o material é oticamente fino (~100 AU) observamos a explosão no visível (~10^{42} J energia em fótons).

Luminosidade no pico ~ 10^{36} W (10^{9} L_{Sol})

SN tipo II são as mais comuns: provavelmente originadas de supergigantes vermelhas.

SN tipos Ib ou Ic: perderam grande parte de seus envoltórios antes da explosão → podem ter se originado de WN ou WC, respectivamente

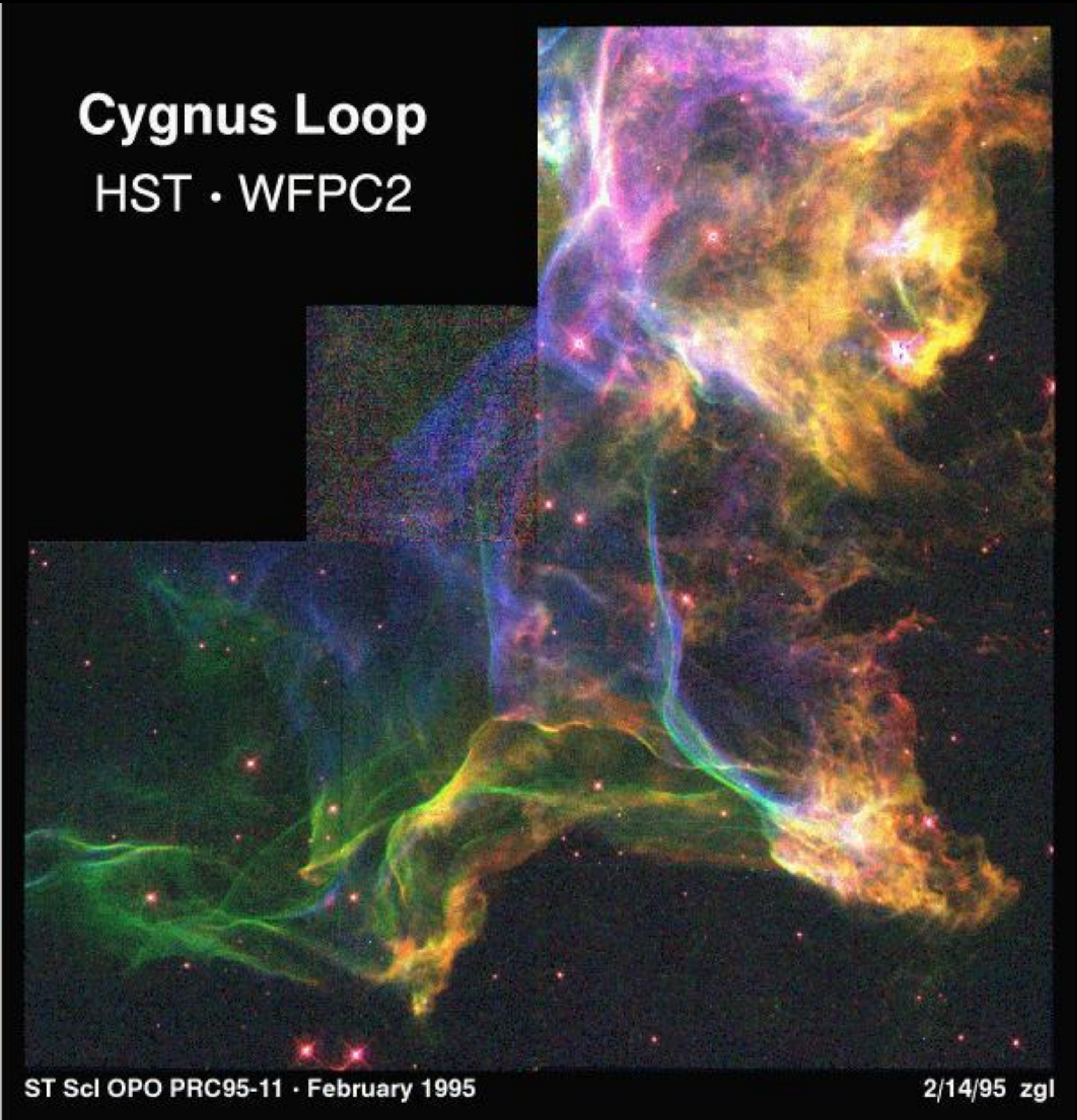
Remanescente estelar de uma SN de colapso de *core*:

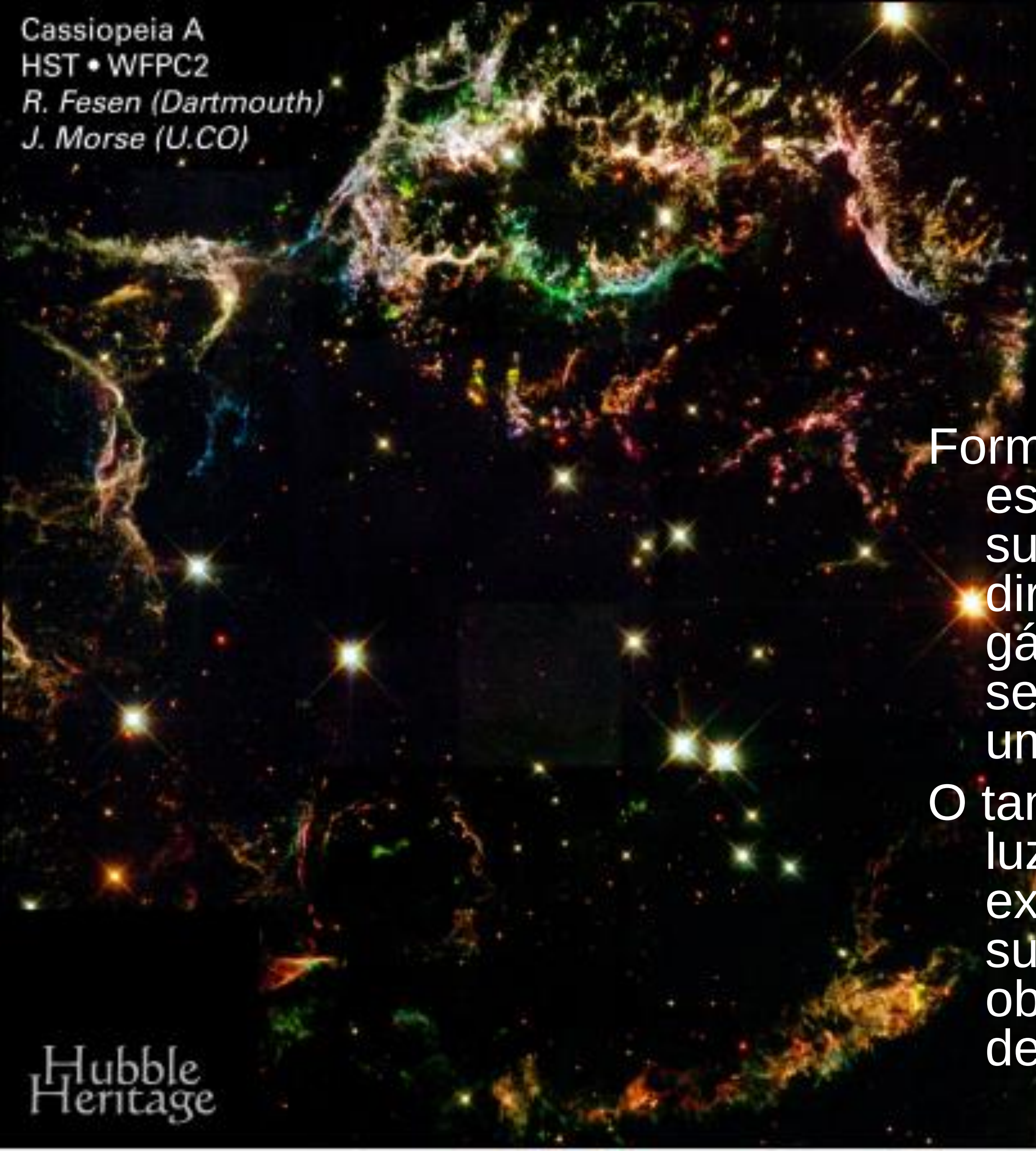
$M_{ZAMS} < 25\ M_\odot$ → pressão dos nêutrons degenerados suporta o colapso → estrela de nêutrons

$M_{ZAMS} > 25\ M_\odot$ → buraco negro

Restos de supernovas (*SNR*)

Em expansão por longos perídos, emitindo radiação syncrotron: e^- espiralam ao redor das linhas de campo magnético.





Cassiopéia A

o *SNR* mais jovem já detetado.

- Formato quase esférico. A borda superior mostra a direção da ejeção do gás assemelhando-se ao rompimento de uma bolha.
- O tamanho (13 anos-luz) indica que a explosão da supernova teria sido observada há cerca de 340 anos

Nucleosíntese e Abundâncas químicas

C, N, O, Ne, Si, S → produzidos em estrelas massivas e ejetados por SN tipo II ou Ib/Ic

Elementos do pico do Fe (Cr, Fe, Co, Ni) → SN Ia

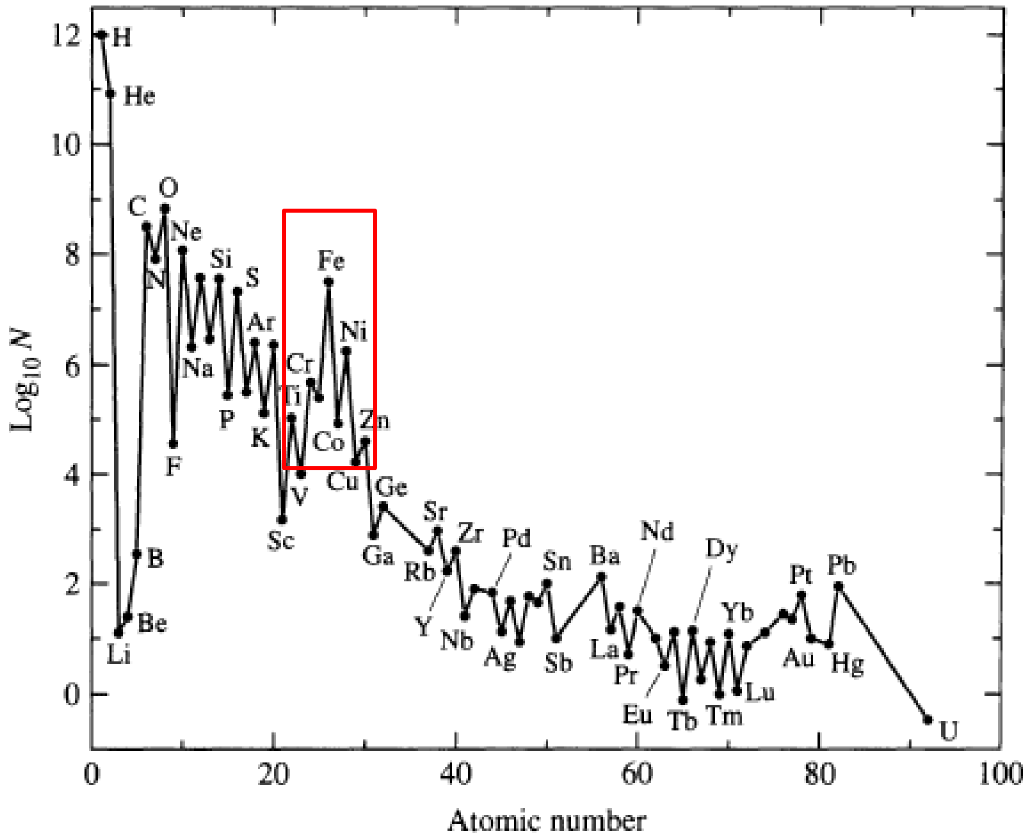
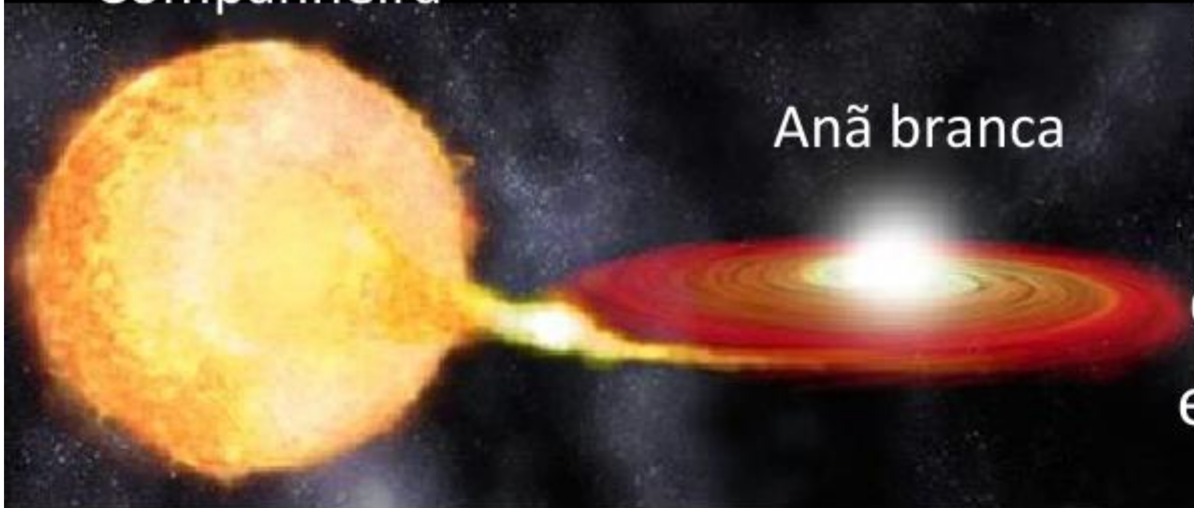


FIGURE 15.16 The relative abundances of elements in the Sun's photosphere. All abundances are normalized relative to 10^{12} hydrogen atoms. (Data from Grevesse and Sauval, *Space Sci. Rev.*, *85*, 161, 1998.)

Companheira



Supernovas de tipo Ia enriquecem quimicamente a Galáxia, em particular em elementos do pico do Fe.

Supernova tipo Ia

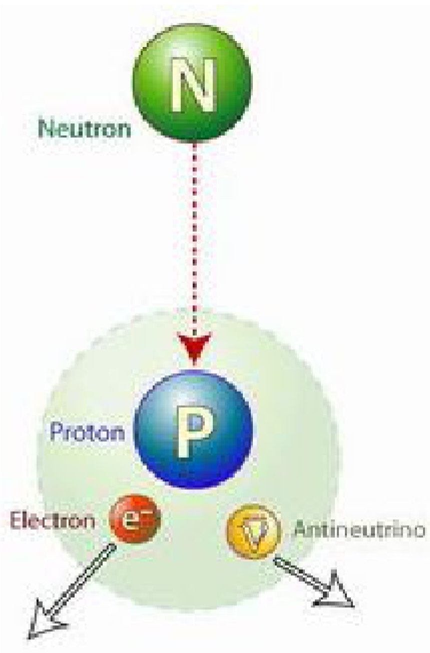
Acontecem quando anãs brancas (massa inicial < $8M_{Sol}$) acrescem massa de companheiras e superam certo limite ($\sim 1,4\ M_{Sol}$)

Nucleossíntese por captura de nêutrons: processo-s e processo-r

Nêutrons não são afetados pela barreira Coulombiana.

$$ {}^{A}_{Z}\mathrm{X} + n \rightarrow {}^{A+1}_{Z}\mathrm{X} + \gamma $$

O Nêutron capturado pode decair → elemento químico com Z = Z+1



$$ {}^{A+1}_{Z}\mathrm{X} \rightarrow {}^{A+1}_{Z+1}\mathrm{X} + e^{-} + \overline{\nu}_e + \gamma $$

Alto fluxo de nêutrons: processo-*r* (rapid)
E.g., supernova

Baixo fluxo de nêutrons: processo-*s* (slow)
Estrelas AGB

15.4 *Gamma ray bursts* (GRB)

- Ocorrem em regiões aleatórias no céu: ~1 por dia.
- Energia desde 1 keV até vários GeV
- Duração: 10^{-2} a 10^{3} s, com tempo de subida de 10^{-4} s e queda exponencial
- Usualmente têm vários picos.
- Exemplos: *Burst and Transient Source Experiment* (BATSE) no *Compton Gamma-Ray Observatory* (CGRO)

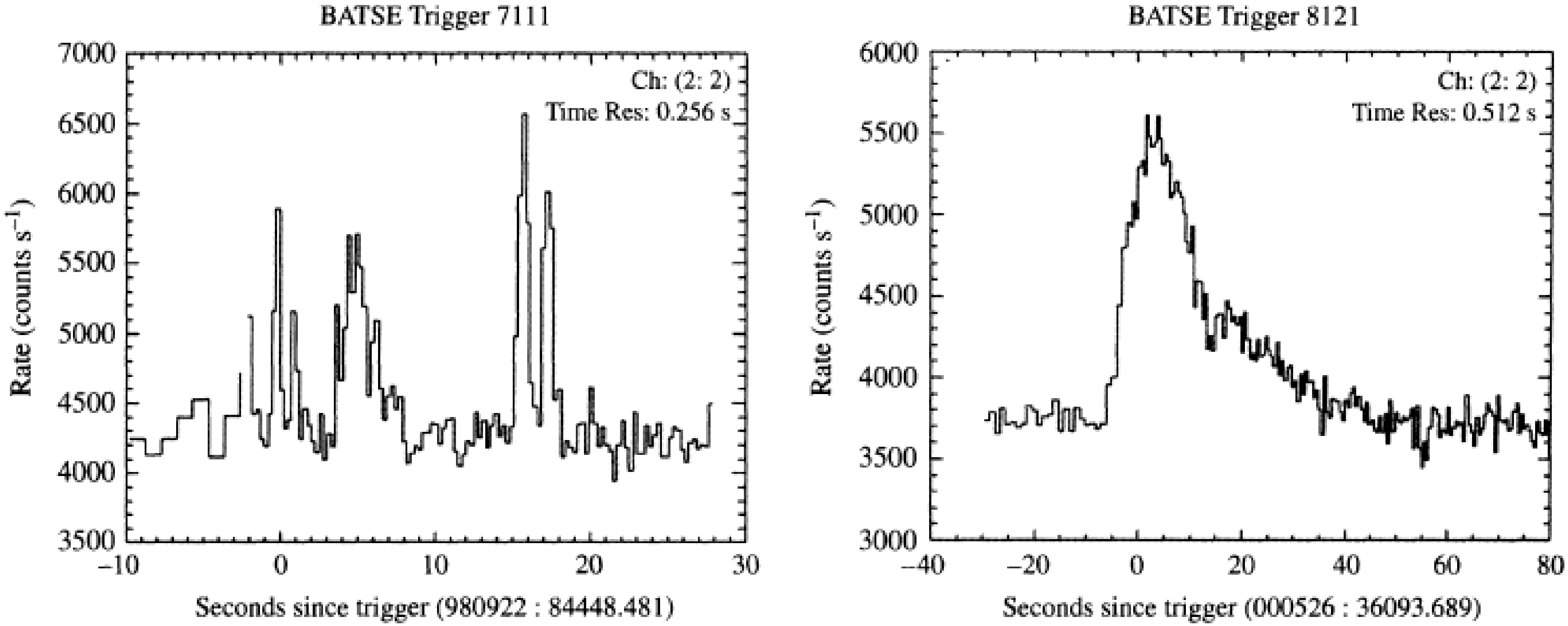
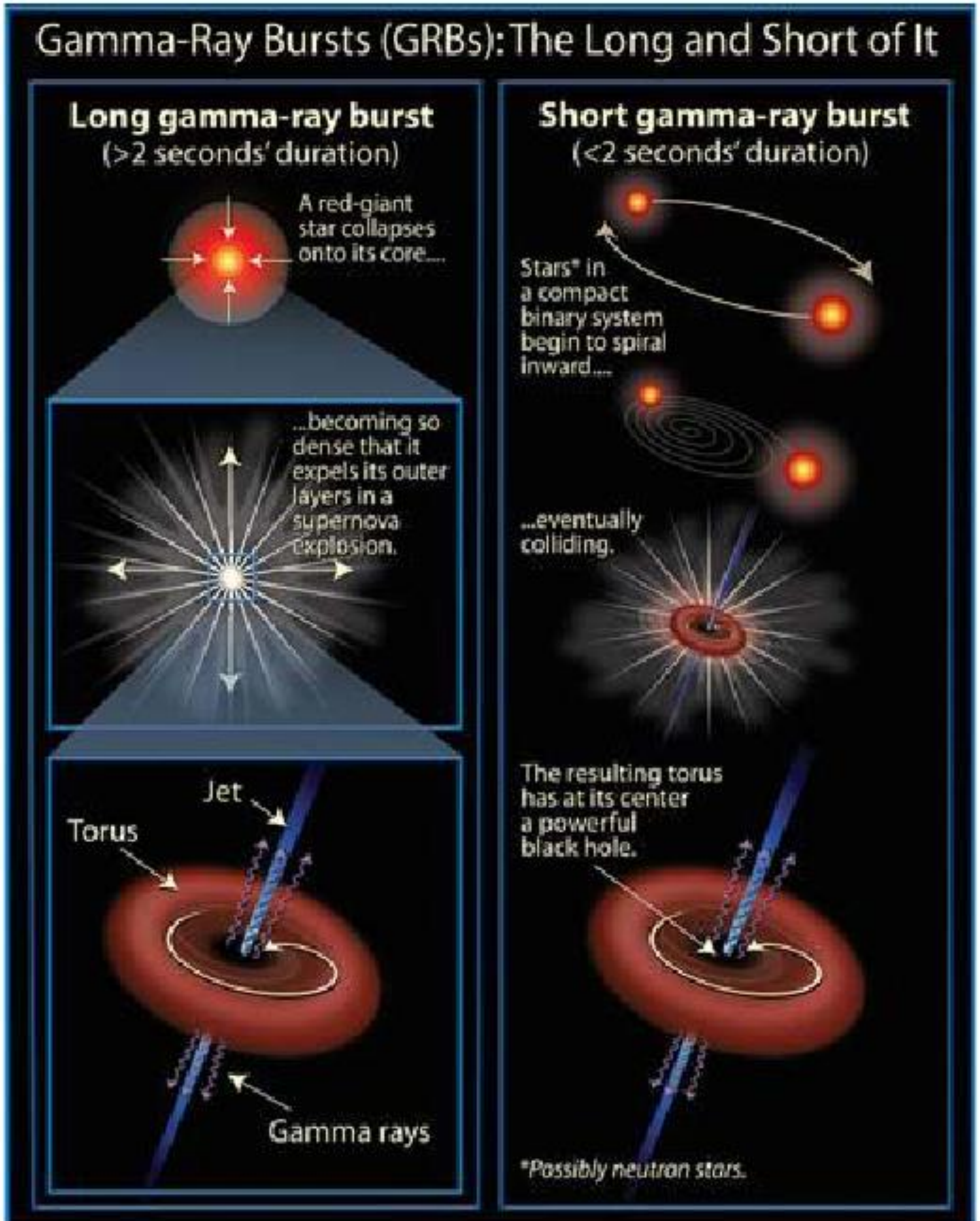


FIGURE 15.17 Light curves of two gamma-ray bursts, GRB 980922 and GRB 000526, in the energy range between 50 keV and 100 keV. The data were obtained by BATSE onboard the Compton Gamma-Ray Observatory. The dates of the two events are recorded in their designations; GRB 980922 occurred on September 22, 1998, and GRB 000526 occurred on May 26, 2000. GRB 0000526 was the last gamma-ray burst recorded by BATSE before the Compton Gamma-Ray Observatory was deorbited. (Courtesy of the BATSE Team – NASA.)

Monitoramento de Explosões de Raios Gama do telescópio Fermi (Fermi GBM) e participação brasileira na notícia sobre colisão de 2 estrelas de nêutrons (ver no Moodle: link para Revista Fapesp).



Dois tipos de GRBs.

Long-soft (> 2 segundos)

Menor energia.

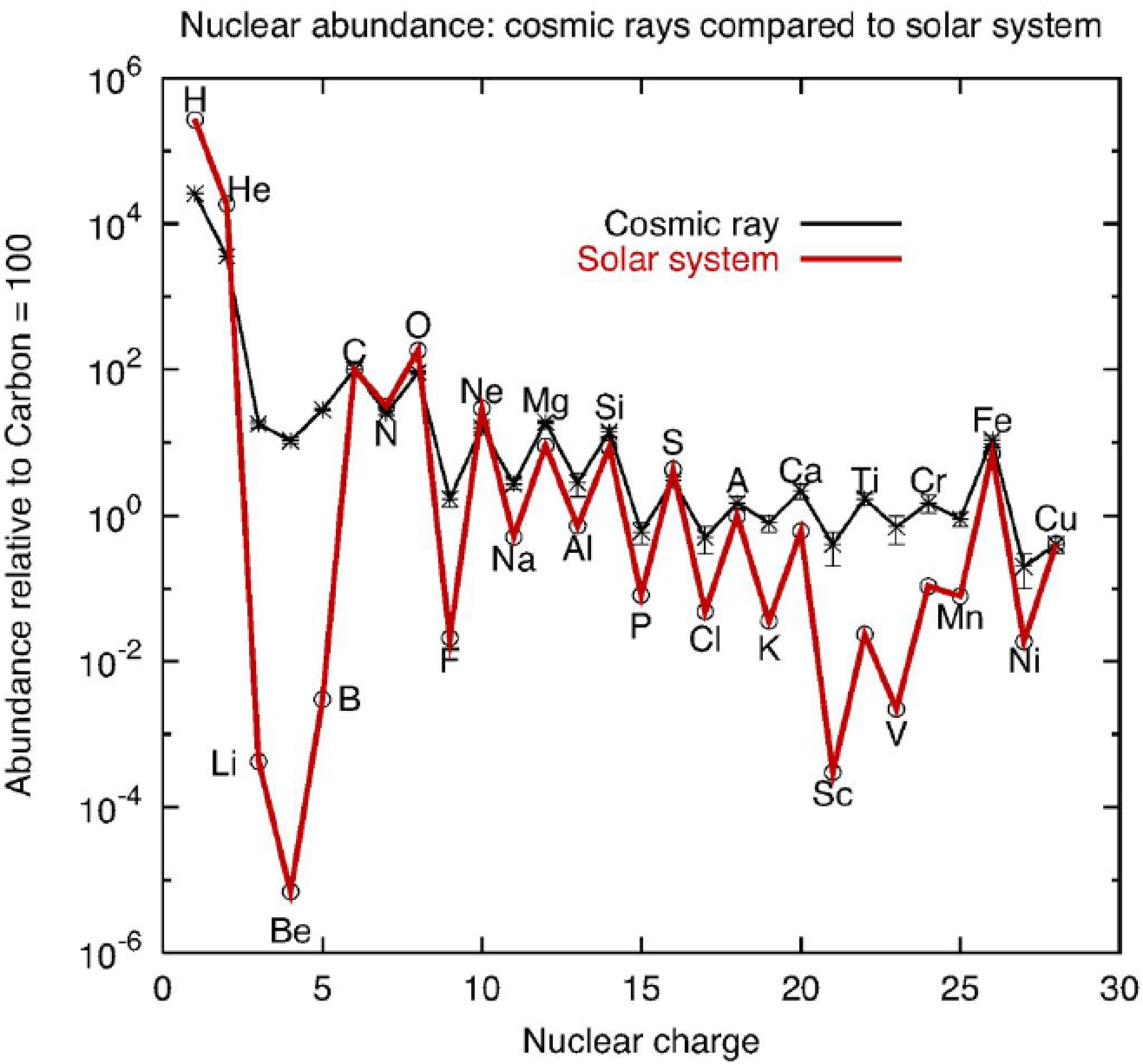
Colapso de supernova.

Short-hard (< 2 segundos)

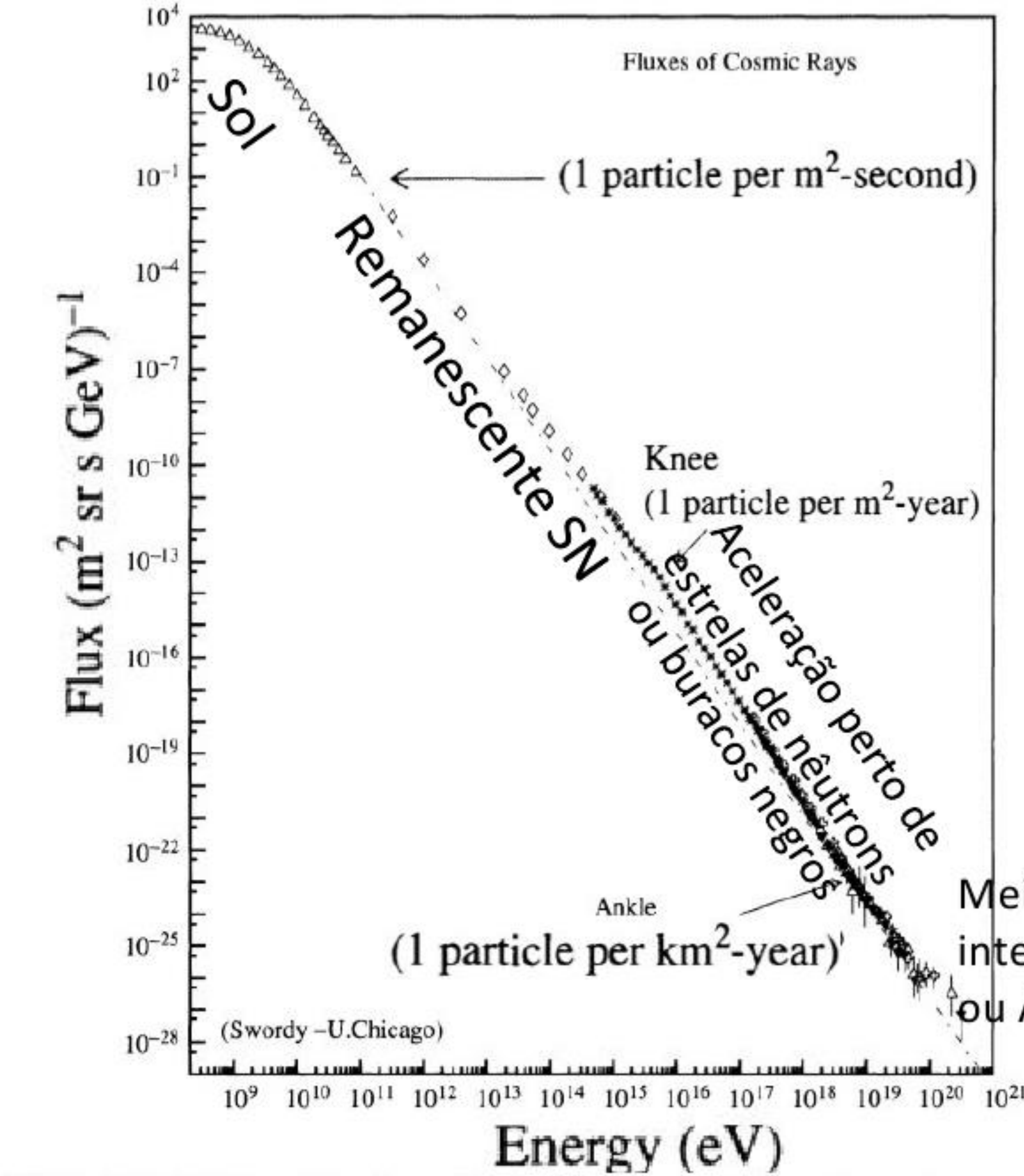
Maior energia.

Colisão de 2 estrelas de nêutrons

15.5 Raios cósmicos. Composição



Li, Be, B podem ser produzidos no ISM devido a colisões com raios cósmicos



Energias:
$10^7 – 3x10^{20}$ eV

FIGURE 15.22 The flux of cosmic rays as a function of energy. (Ref: J. Cronin, T. K. Gaisser, and S. P. Swordy, *Sci. Amer.*, *276*, 44, 1997.)

Próxima aula

- Cap.16 Objetos compactos (remanescentes degenerados de estrelas)