STELLAR NUCLEOSYNTHESIS

- EVOLUTION OF STARS CHANGES THEIR CHEMICAL COMPOSITION
- EJECTION OF MATERIAL CHANGES COMPOSITION OF INTERSTELLAR GAS
- STARS FORMED FROM THIS GAS HAVE THE CHANGED COMPOSITION

- MAIN SEQUENCE STARS

ATMOSPHERE HAS COMPOSITION OF NATAL CLOUD

- YOUNG M-S STARS HAVE COMPOSITION OF PRESENT INTERSTELLAR GAS

- OLD M-S STARS HAVE COMPOSITION OF INTERSTELLAR GAS OF LONG AGO

'OLD' ≡ 'METAL-POOR' (relative to now)

- EVOLVED (RED GIANTS, ...) STARS MAY HAVE MIXED PRODUCTS OF INTERNAL NUCLEAR PROCESSES INTO THEIR ATMOSPHERE.

TECHNETIUM IN ASYMPTOTIC GIANTS

STELLAR ORIGINS OF ELEMENTS

- **THERMONUCLEAR FUSION REACTIONS**

$H \rightarrow He, C, N, O, \ldots Fe$ { MASSIVE STARS, SN II

$H \rightarrow He, C, N, O$ LOW MASS STARS

$He \rightarrow$ "Fe" SNIa (EXPLODING WHITE DWARFS)

- NEUTRON CAPTURE REACTIONS

$Fe + n \rightarrow \ldots + n \rightarrow + n \ldots \rightarrow$

SLOWLY in LOW MASS RED GIANTS

RAPIDLY in SN II

ORIGINS OF THE CHEMICAL ELEMENTS

- **BIG BANG** (3 minutes)

  H, He, Li: ONLY

- **STARS** (then to now ...)

  'ALL' OTHER CHEMICAL ELEMENTS

- **COSMIC RAYS IN INTERSTELLAR GAS**

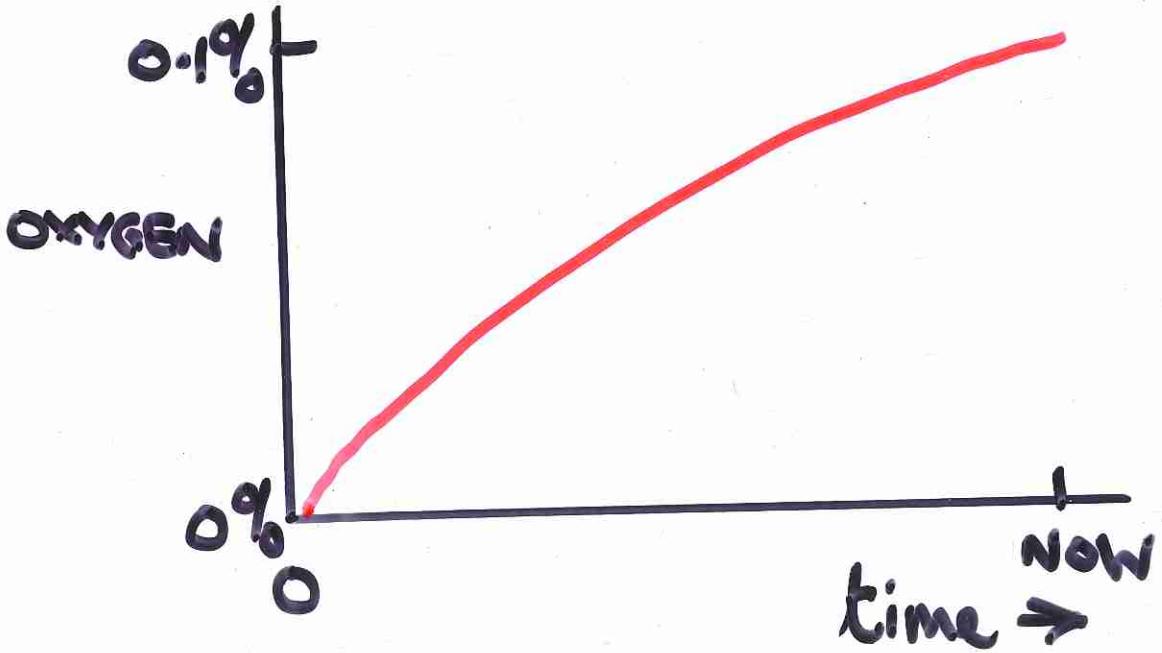
  Li, Be, B

LONG (10^{10} yrs) AGO,

GAS WAS 90% H 10% He 0% else

NOW,

GAS IS 88% H 11% He 1% else



OXYGEN CONTENT INCREASED BY EJECTA FROM MASSIVE STARS

WATER , H_2O

BIG BANG

MASSIVE STARS before SN II

PLATINUM, GOLD, URANIUM

MASSIVE STARS IN SN II EXPLOSION

ZIRCON

LOW MASS STARS by NEUTRON CAPTURE IN RED GIANTS

BERYL (BERYLLIUM)

COSMIC RAYS IN INTERSTELLAR GAS

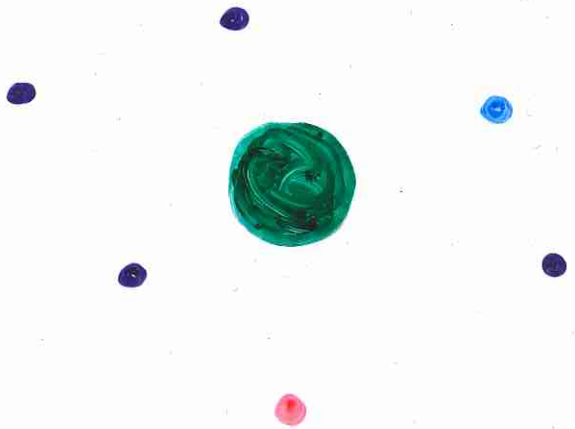
$p + O \rightarrow Be + bits$

GAMMA-RAY BURSTS

- **DISCOVERY**
  - RESULT OF 1960s TEST-BAN TREATY

US, FRENCH, USSR SATELLITES
to detect γ-rays from
illegal H-bomb tests in space

"VELA"



- BURSTS SEEN but not from H-bombs
  but from outside solar system

PUBLIC NOT TOLD UNTIL 1973!!

- **POSITIONS ON SKY NOT ACCURATELY DETERMINED**

  γ-RAY DETECTORS LACKED DIRECTIONAL SENSITIVITY – not necessary (!), difficult to achieve.

  POSITIONS DETERMINED from DELAYS IN ARRIVAL TIMES AT DIFFERENT SATELLITES

- COMPTON γ-RAY OBSERVATORY [1991]
  - IMPROVED POSITIONS but NOT accurate for identification at other (optical) wavelengths.

DEGREES!

  - ~1 burst per day
  - bursts lasts ~1/10 – 500 seconds
  - very few (none?) repeat bursts.
  - ISOTROPIC

MANY THEORIES (as many as # of bursts!)
- LOCAL
- V. DISTANT

compare γ-ray burst sky with radioactive Al sky.

LONG BURST

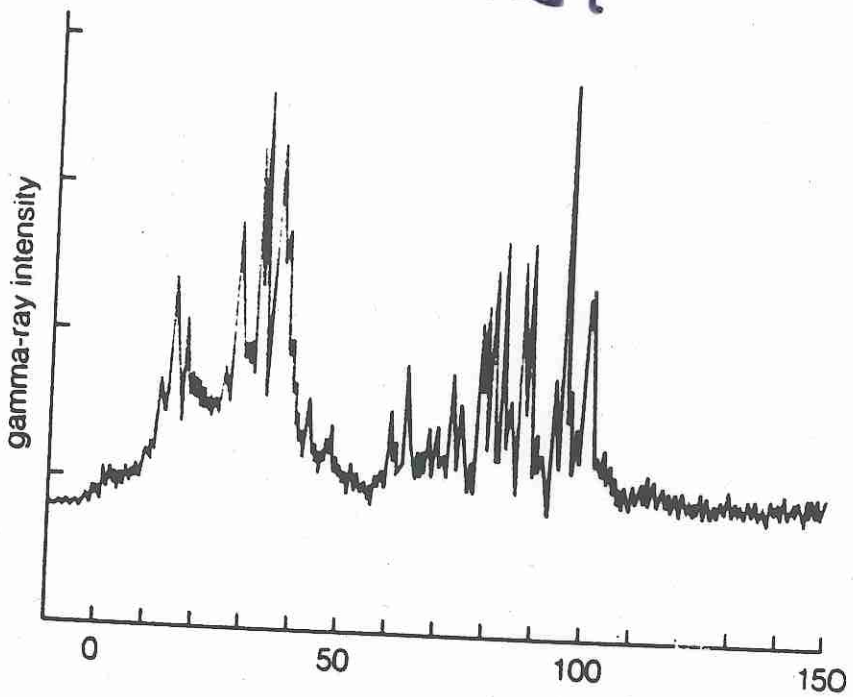
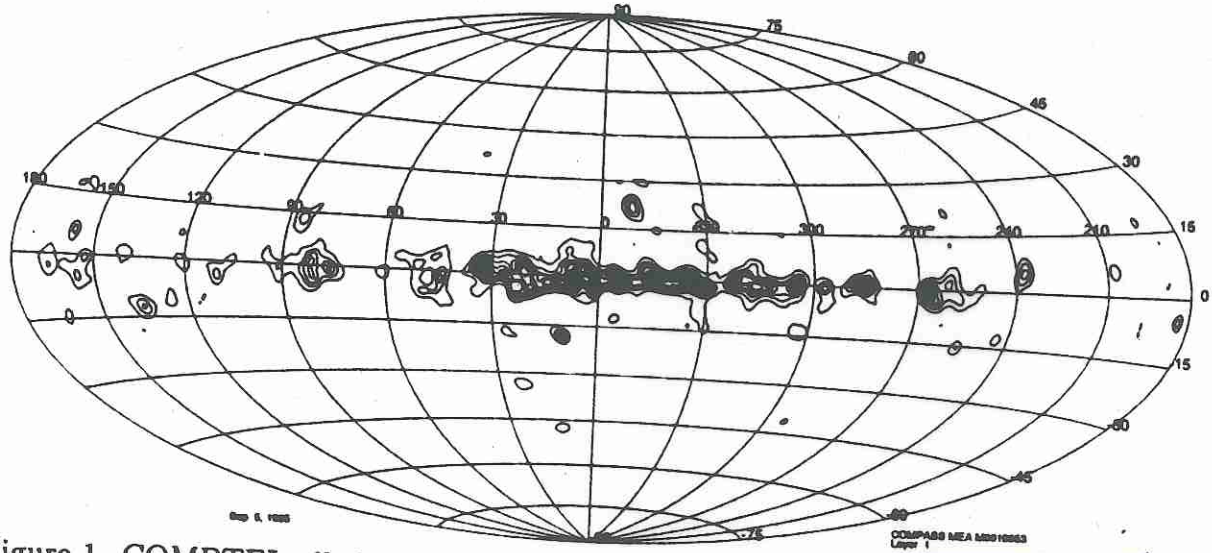


FIGURE 17.16 A typical gamma-ray burst light curve.

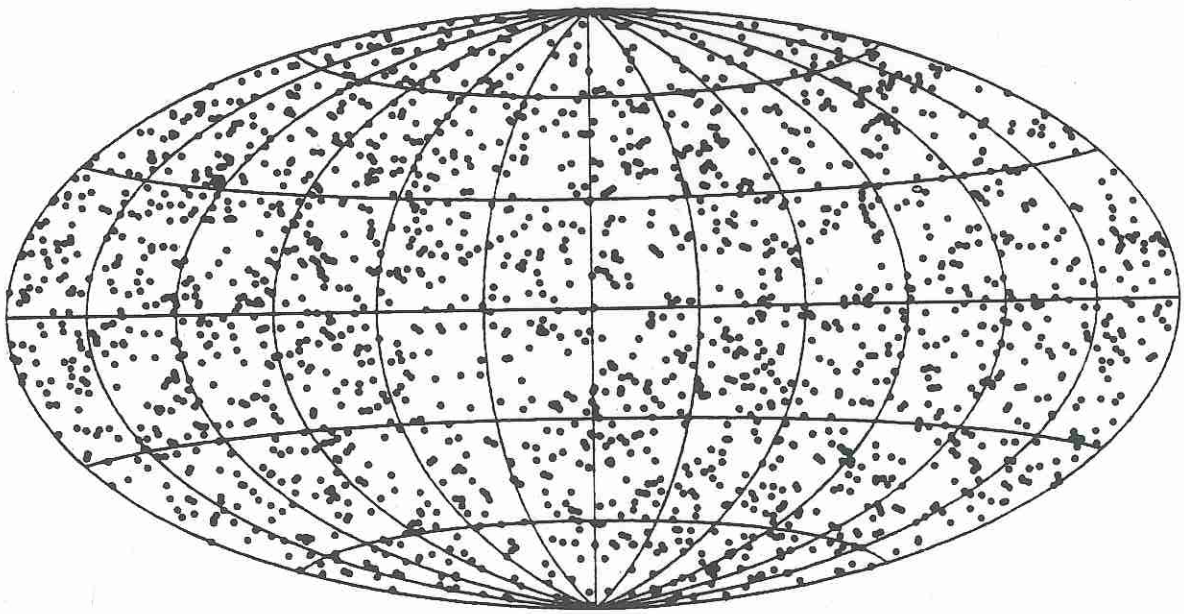
+

SHORT BURST (~1 SEC)



MILKY WAY

Figure 1. COMPTEL all-sky image of 1.809 MeV emission from radioactive ^{26}Al [3]



DISTRIBUTION OF γ-RAY BURSTS ON SKY

LOCATION, LOCATION, LOCATION

- BEPPO SAX x-ray satellite [1996]
  - BEPPO: NICKNAME OF FAMOUS ITALIAN SCIENTIST
  - SAX: SATELLITE per ASTROMIA X
  - INTENT TO DETECT γ-RAY BURSTS by x-ray AFTERGLOW
  - LOOKS AT 5% OF SKY AT ANYTIME
    - PICKS UP - BY CHANCE - A γ-BURST ROUGHY 1 EVERY 20 DAYS
    - LOCATES x-ray position to ~1' (1/30 MOON DIAMETER)
    - SENDS POSITION TO OPTICAL TELESCOPES QUICKLY - PRONTO -

- 1997 FEB 28 near ORION
  - X-ray AFTERGLOW ~ 8 HOURS AFTER BURST
  - POSITION SENT OUT

BURST appeared at edge of "fuzz" (= galaxy?)

- 1997 MAY 8
  - A COUPLE OF HOURS AFTER γ-RAY BURST
    OPTICAL TELESCOPES CAUGHT AFTERGLOW

→ GALAXY at 4 billion LYs

- **FASTER RESPONSE NOW!**
  1999 JAN 23 BURST of 110 SECONDS AND OPTICAL IMAGES TAKEN WHILE BURST WAS IN PROGRESS!

→ GALAXY at 9 bill. LYs.

NOT LOCAL AT ALL!

WHAT ARE THEY?

SEEDS
§14-3
pp 314-317

- BURST AT 10 BILL. YRS HAS $L \sim 10^{16} L_\odot$, if ISOTROPIC
  BEAMED? (LIGHTHOUSE)
- LONG BURSTS = MASSIVE STAR
  HYPERNOVA: COLLAPSE DOWN POLAR AXIS → BEAMING

SHORT BURSTS = NEUTRON STAR
+ STRONG MAGNETIC FIELD ?
+ BINARY?

MODEL has to account for
1 BURST / day

MODEL

- A SMALL AMOUNT ($10^{-5} M_\odot$) OF MASS EJECTED AT SPEED OF LIGHT (e^-, e^+) AS A FIREBALL
- FIREBALL PLOWS INTO INTERSTELLAR GAS → HEATING IT (x-rays, optical...)

THERE ARE OTHER IDEAS!

NOT TOO LOCAL - we hope!

NEUTRON STAR PAIR merge

→ γ-ray BURST

SUPPOSE at 1600 LY

BLAST & γ-RAYS ≡ 10,000 MEGATON BOMB

- NITRIC OXIDE → ACID RAIN

→ OZONE DESTROYED

→ SOLAR UV AT EARTH ↑

COULD BE CLOSER .....

STELLAR REMNANTS

INITIAL MASS	FATE
$\geq 8 M_{SUN}$	TYPE II SN leaving a NEUTRON STAR or a BLACK HOLE
$0.8 - 8 M_{SUN}$	RED GIANT WIND leaving a WHITE DWARF
$0.5 - 0.8 M_{SUN}$	WILL EVOLVE EVENTUALLY BUT MAIN SEQ. LIFETIME > AGE OF GALAXY

FINAL FORMS

WHITE DWARF

- $m \leq 1.4 M_{sun}$
- SUPPORTED AGAINST GRAVITY BY DEGENERATE ELECTRONS, EVEN AS $T \to 0$

NEUTRON STAR

- $m < (2\text{-}3) M_{sun}$
- DEGENERATE NEUTRON PRESSURE

BLACK HOLE

- $m > (2\text{-}3) M_{sun}$?
- CONTINUOUS GRAVITATIONAL COLLAPSE

NEUTRON STARS

THEORY preceded OBSERVATION

1932: NEUTRON DISCOVERED

JAMES CHADWICK / CAVENDISH LAB

1934: NEUTRON STARS PREDICTED

WALTER BAADE / FRITZ ZWICKY

– DEGENERATE NEUTRON PRESSURE

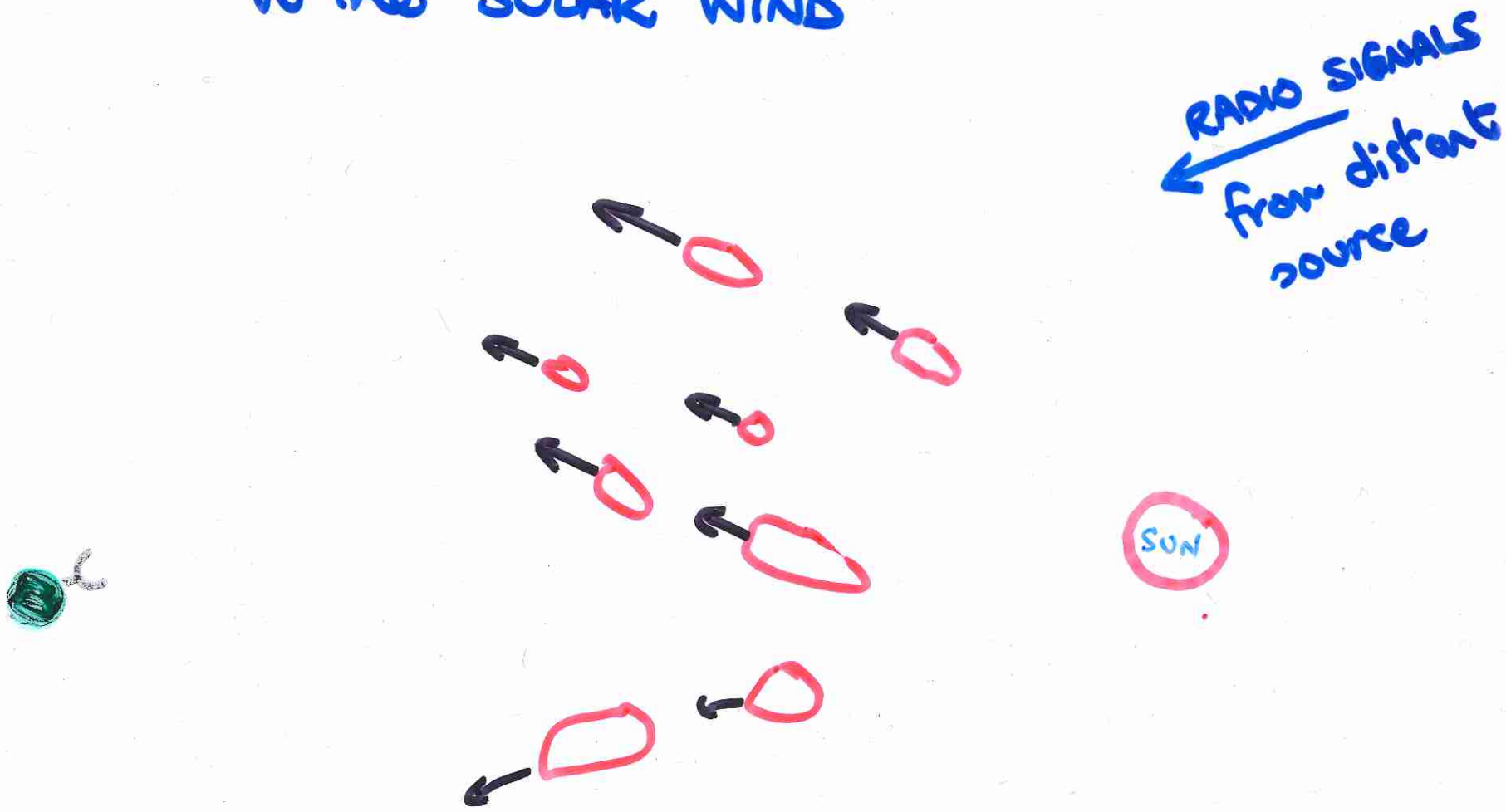
"WE ADVANCE THE VIEW THAT SNe REPRESENT THE TRANSITION FROM ORDINARY STARS INTO NEUTRON STARS..."

BAADE IDENTIFIES POSSIBLE NEUTRON STAR IN CRAB NEBULA, = SN from AD1054.

1938: MORE DETAILED CALCULATIONS ON NEUTRON STARS by OPPENHEIMER + VOLKOFF, ... AND LEV LANDAU

WORLD WAR II

HEWISH was measuring clumps of ionized gas in the SOLAR WIND



- CLUMPS deflect radio signals
- RECORDED SIGNAL fluctuates RAPIDLY

∴ DESIGNED TELESCOPE to RESPOND to RAPID VARIATIONS

"PROPHETIC PROPOSAL WAS POLITELY IGNORED BY MOST SCIENTISTS FOR YEARS"

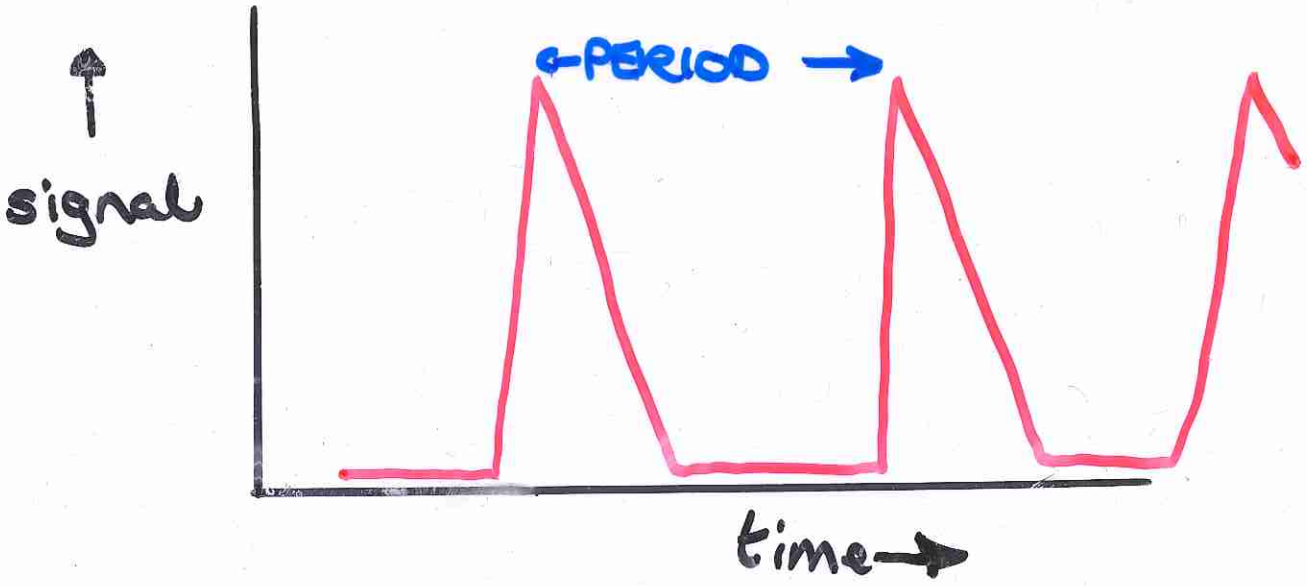
1967 RADIO PULSARS discovered

BELL & HEWISH - serendipitously using telescope built to measure RADIO SOURCE SCINTILLATION

PULSARS DETECTED AS REGULAR PULSES

- TERRESTRIAL SOURCE ELIMINATED
- DOPPLER SHIFTS - EARTH'S MOTION
- FIXED LOCATION ON CELESTIAL SPHERE

RADIO PULSARS DISCOVERED



PERIODS: milliseconds to ~1 to 2 seconds

Periods slowly lengthen: conservation of energy: rotating * slowing down

'Glitches': starquake - stressed crust breaks.

Millisecond pulsars (1-10 milliseconds): spun-up neutron stars in binary systems

companion donates mass to pulsar

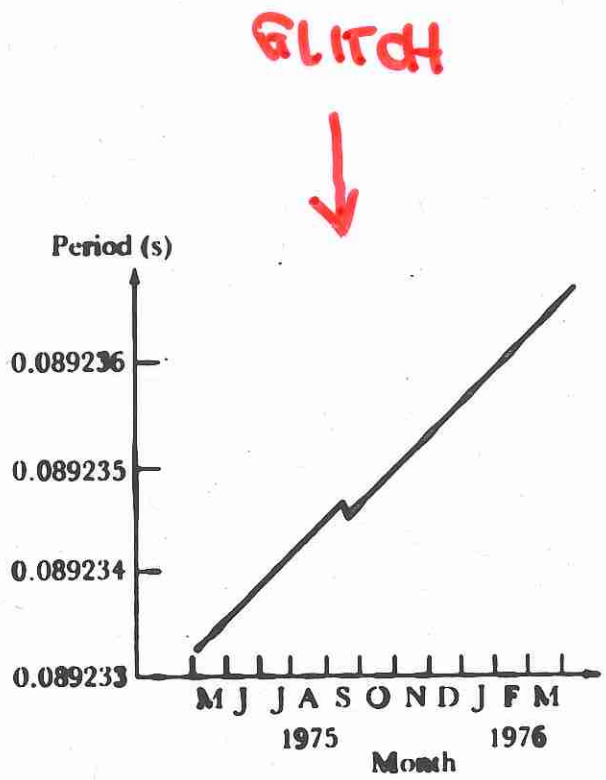


Figure 23-8 A glitch of the Vela pulsar *This graph shows how the period of the Vela pulsar increased suddenly during September 1975. The speedup, called a glitch, is probably caused by a starquake, during which the star's crust cracks and settles.*

A FEW PULSARS HAVE OPTICAL COUNTERPARTS

- FAST, YOUNG PULSARS
  - CRAB PULSAR
  - VELA PULSAR

  } SN REMNANTS

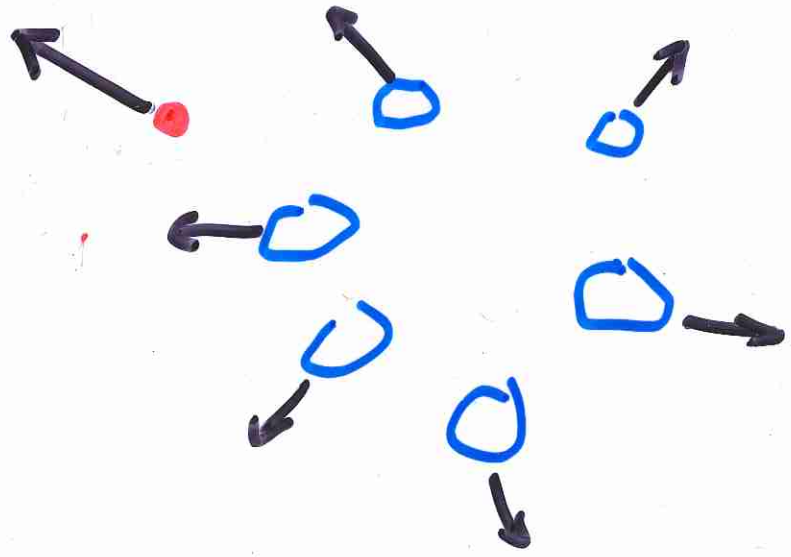
- NEUTRON STAR + SN REMNANT

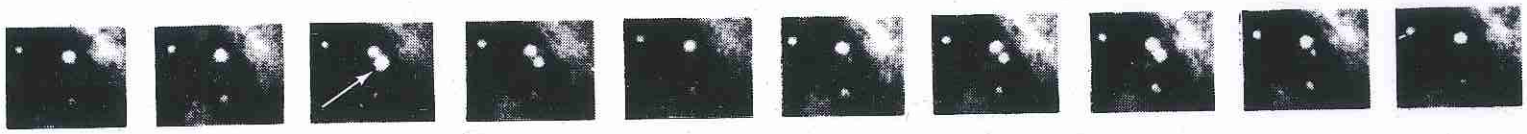
  PROOF THAT SN II (MASSIVE STAR)

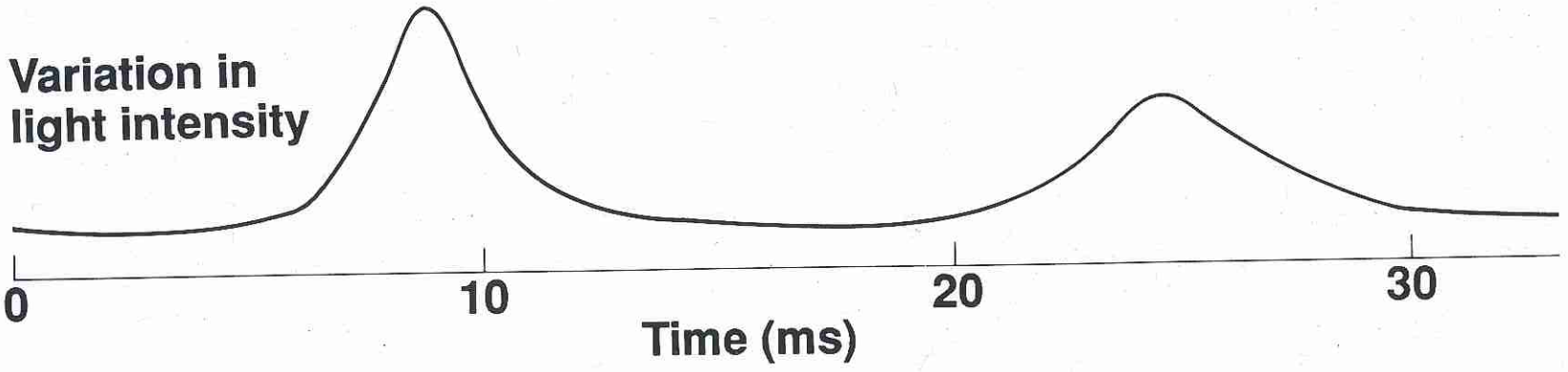
  → NEUTRON STAR

VERY FEW PULSARS ASSOCIATED WITH SN REMNANTS – WHY?

- SN Ia REMNANTS – NO NEUTRON STAR
- GAS OF SN EJECTA DISPERSES & MIXES WITH INTERSTELLAR GAS
- NEUTRON STARS/PULARS BORN WITH A 'KICK'







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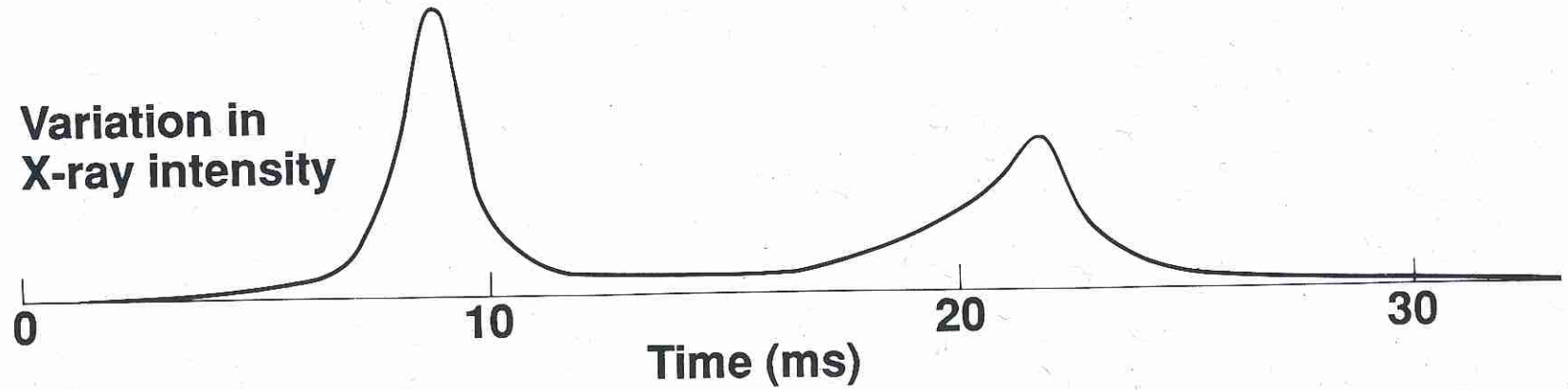

b

Crab nebula pulsar

Seeds/Horizons, 3rd ed., Fig. 11-7; Foundations of Astronomy, 1990 ed., Fig. 14-6