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

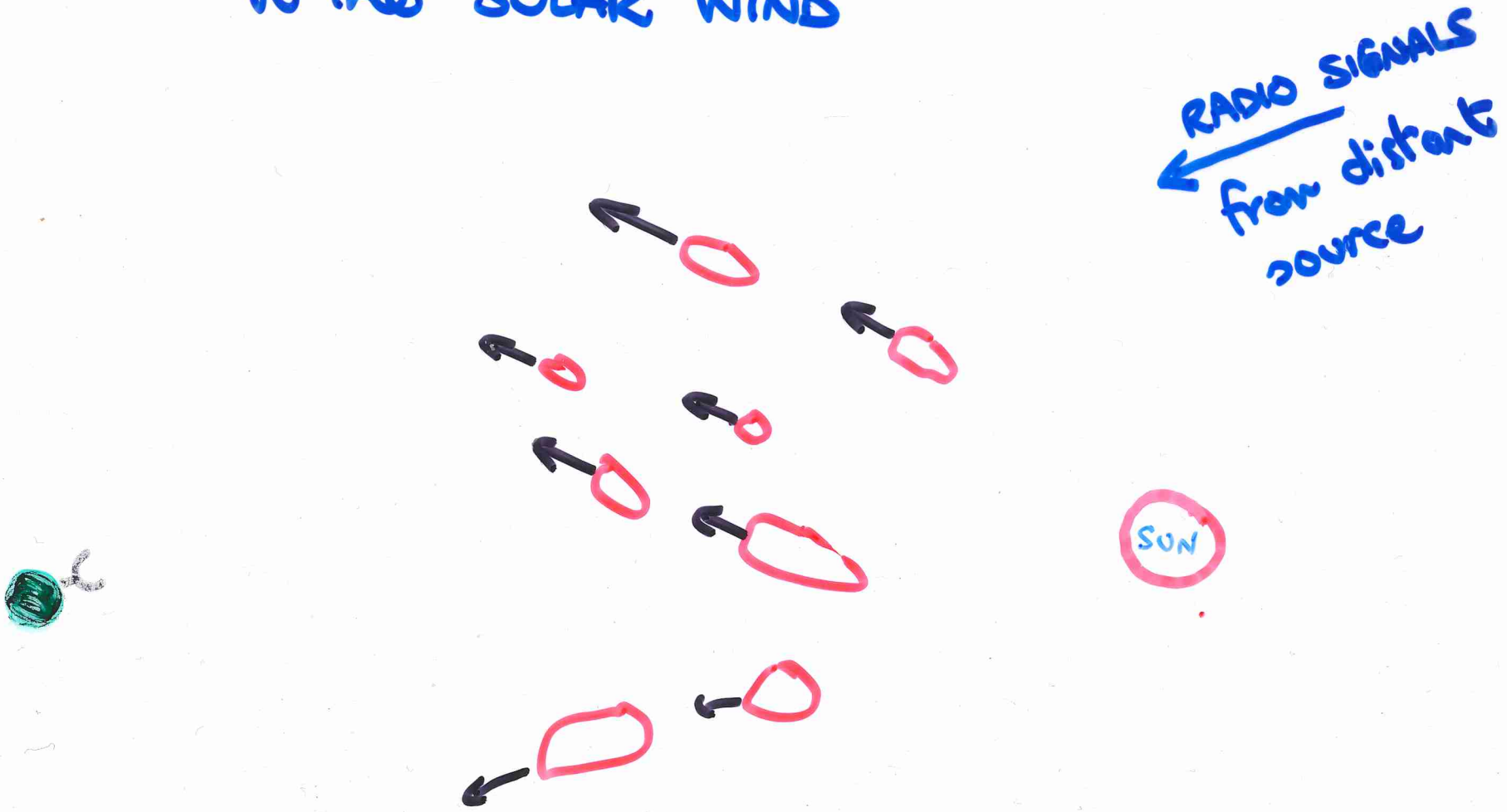
1967 RADIO PULSARS discovered

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

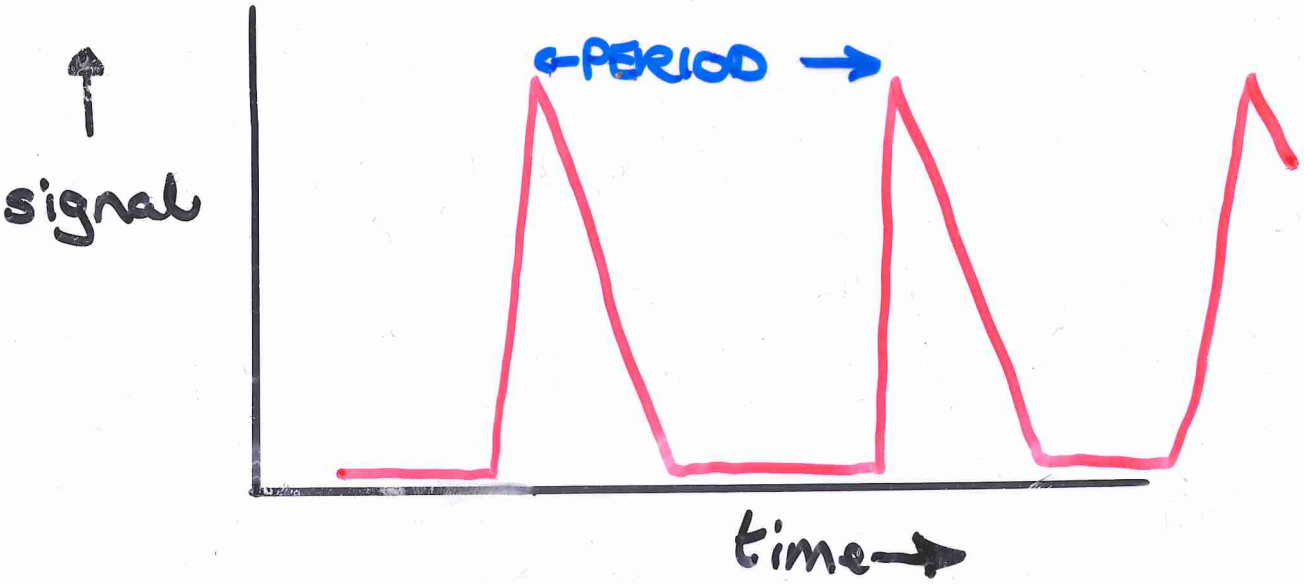
HEWISH was measuring clumps of ionized gas in the SOLAR WIND



- CLUMPS deflect radio signals
- RECORDED SIGNAL fluctuates RAPIDLY

∴ DESIGNED TELESCOPE to RESPOND to RAPID VARIATIONS

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 millisecs): spun-up neutron stars in binary systems

companion donates mass to pulsar

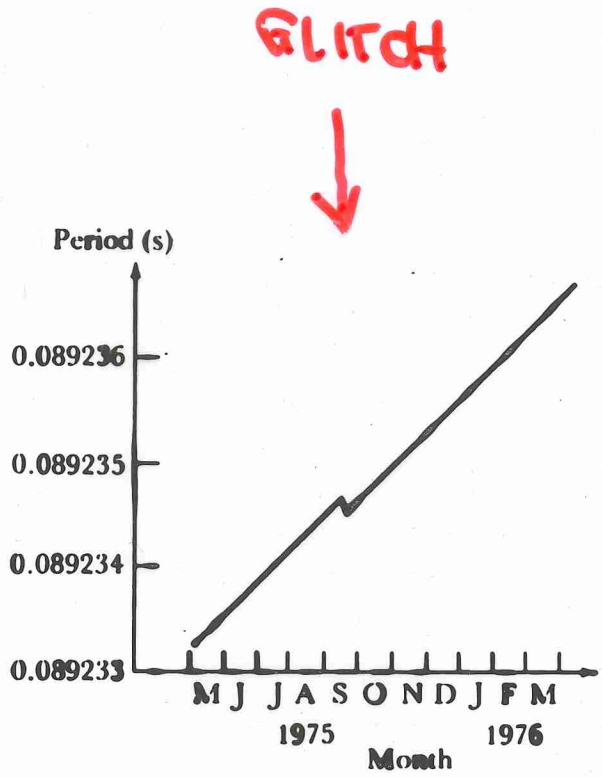


Figure 23-8 A glitch of the Vela pulsar *This graph shows how the period of the Vela pulsar increased suddenly during September 1975. The speedup, called a glitch, is probably caused by a starquake, during which the star's crust cracks and settles.*

A FEW PULSARS HAVE OPTICAL COUNTERPARTS

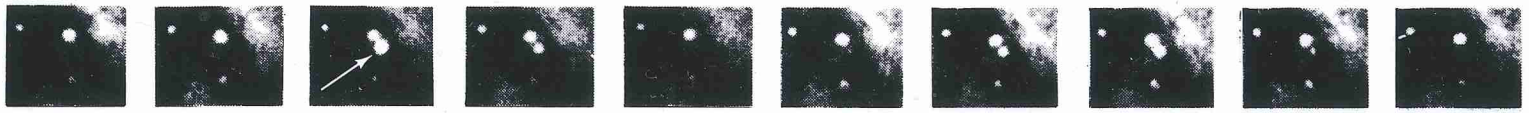
- FAST, YOUNG PULSARS
  - CRAB PULSAR
  - VELA PULSAR

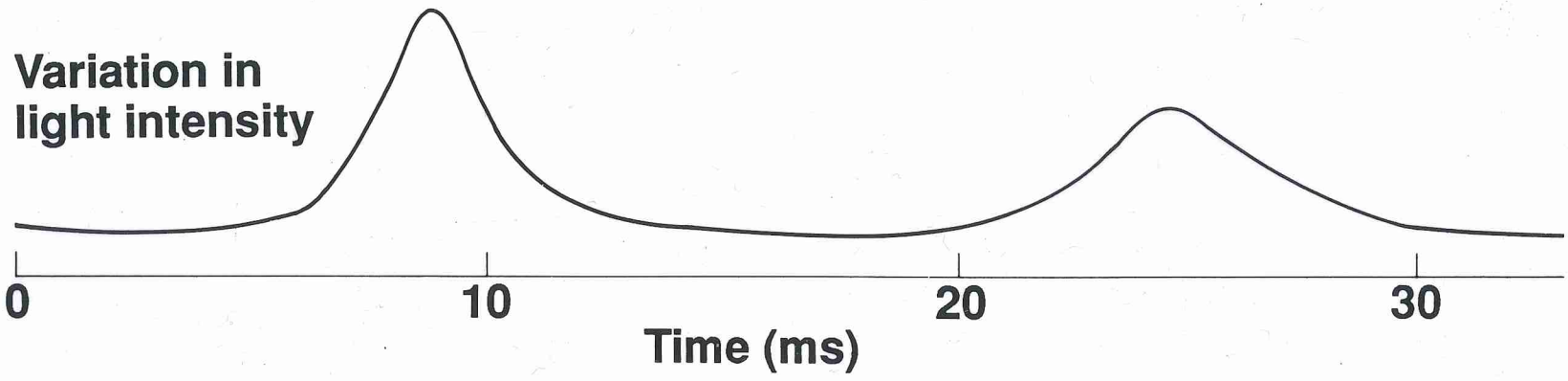
  } SN REMNANTS

- NEUTRON STAR + SN REMNANT

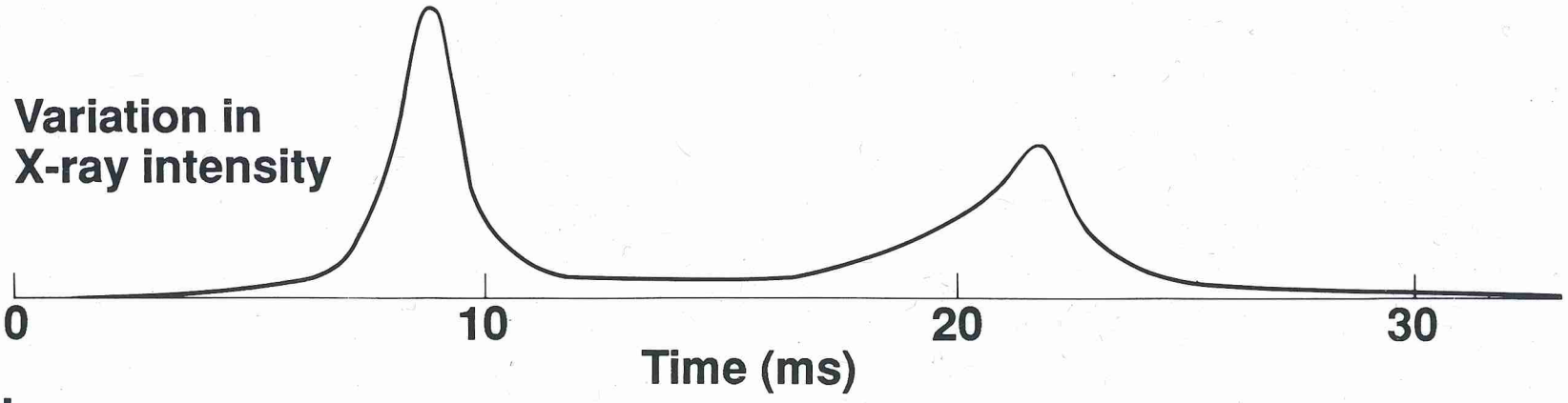
  PROOF THAT SN II (MASSIVE STAR)

  → NEUTRON STAR





a



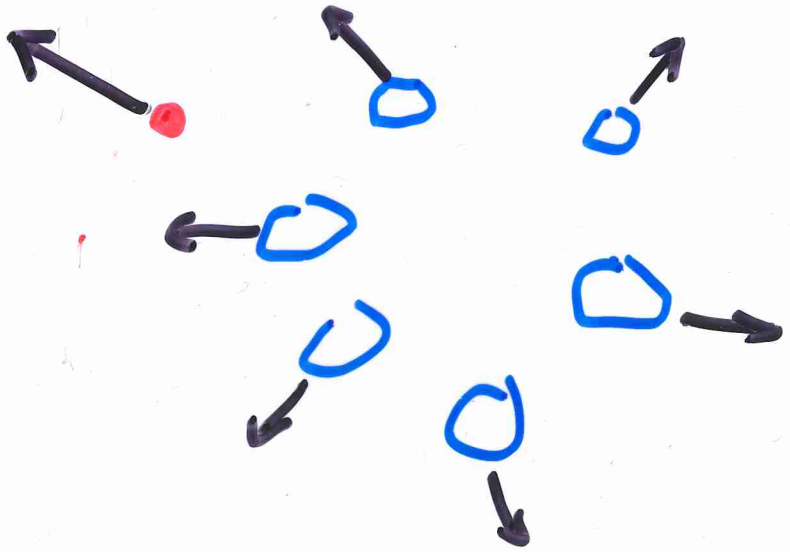
b

Crab nebula pulsar

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

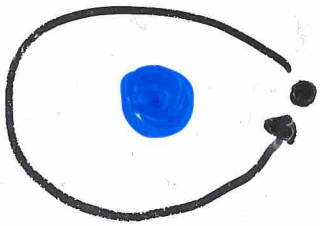
VERY FEW PULSARS ASSOCIATED WITH SN REMNANTS – WHY?

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



CLUES TO IDENTITY OF PULSARS

- IN GALACTIC PLANE (MILKY WAY)
  ∴ PROBABLY STARS NOT GALAXIES
- VERY REGULAR PULSES (STABLE CLOCK)
  - PULSATION?
    WD $t > 1^{sec}$; NS $t < 1/100^{sec}$
  - ORBITAL MOTION?



WD is too big ∴ t too long

NS - orbit decays quickly by gravitational radiation (BINARY PULSAR)

  - ROTATION?

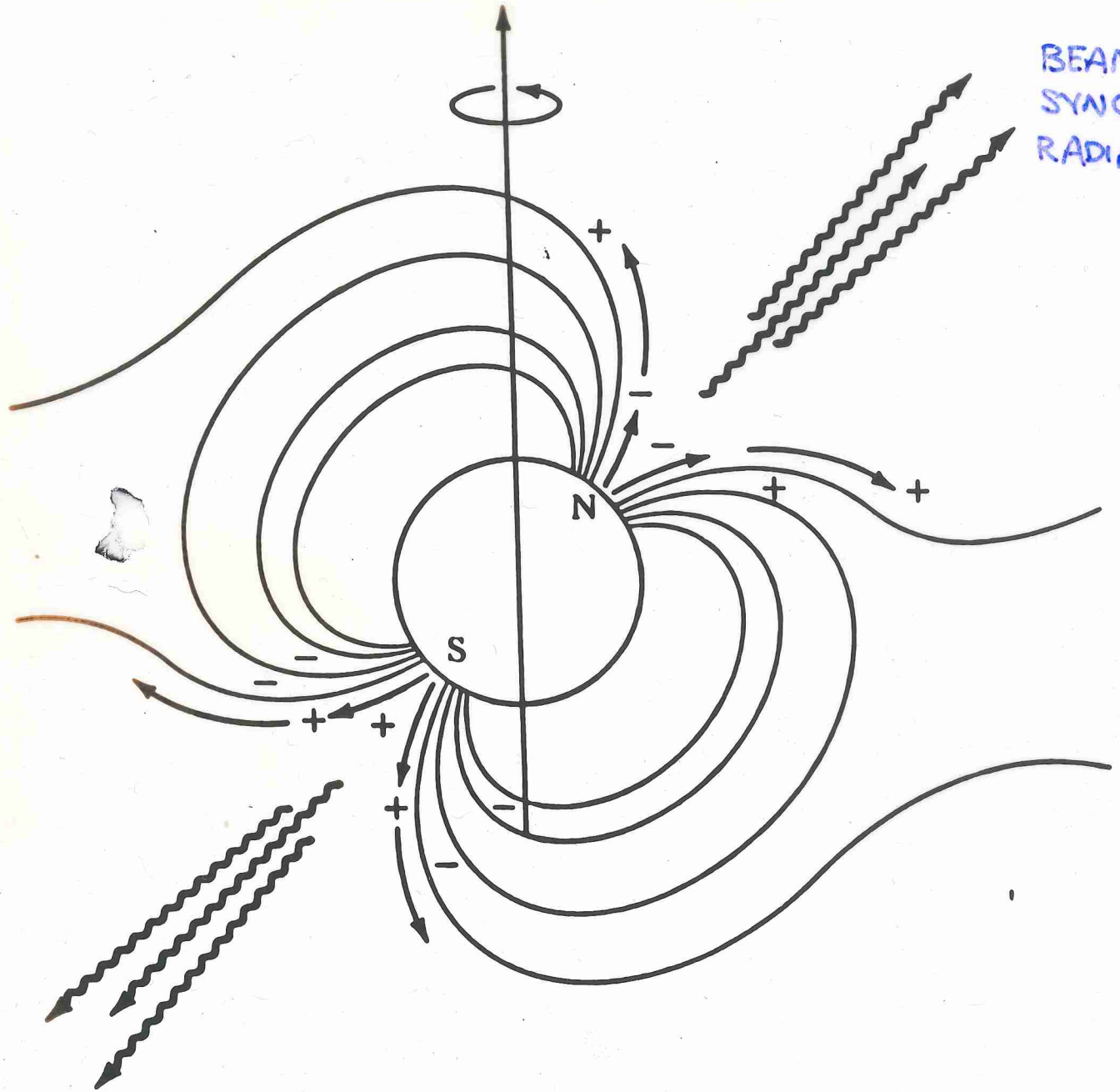
WD too big

NS just right

SPUN-UP BY COLLAPSE IN SI

EVIDENCE THAT PULSARS ARE SPINNING NEUTRON STARS:

1. PULSE INTERVAL GRADUALLY INCREASES – EXPECT THIS AS ENERGY LOST.
2. SOMETIMES PULSE INTERVAL SHORTENS. PREDICTED AS CRUST OF NS SUFFERS STARQUAKES
3. PULSAR FOUND IN CENTER OF CRAB AND VELA SUPERNOVAE REMNANTS



BEAMED SYNCHROTRON RADIATION

GOLDREICH + JULIAN (1969)

ROTATING MAGNETIC → FIERCE ELECTRIC FIELDS → P, e^- PULLED OUT OF SURFACE → BEAMS → RADIATION

LIGHTHOUSE BEACON

ROTATION & MAGNETIC AXES NOT ALIGNED

NEUTRON STARS

- **MASS** $\lesssim 3 M_\odot$ — NEUTRONS BROKEN UP AT HIGH PRESSURE → BLACK HOLE
- **RADIUS** ~15 km (A CITY!) — depends on mass
- **FORMATION** Core collapse in massive star as it SN.

  Young NS is v hot (~100 MILLION K) but cools v. rapidly: seen as X-ray source.

- **FINAL FORM** Supported by degenerate neutron pressure

  NEUTRONS CAN'T DECAY

  $n \not\Rightarrow e^- + p + \bar{\nu}_e$

  CAN'T FIND A 'HOLE'

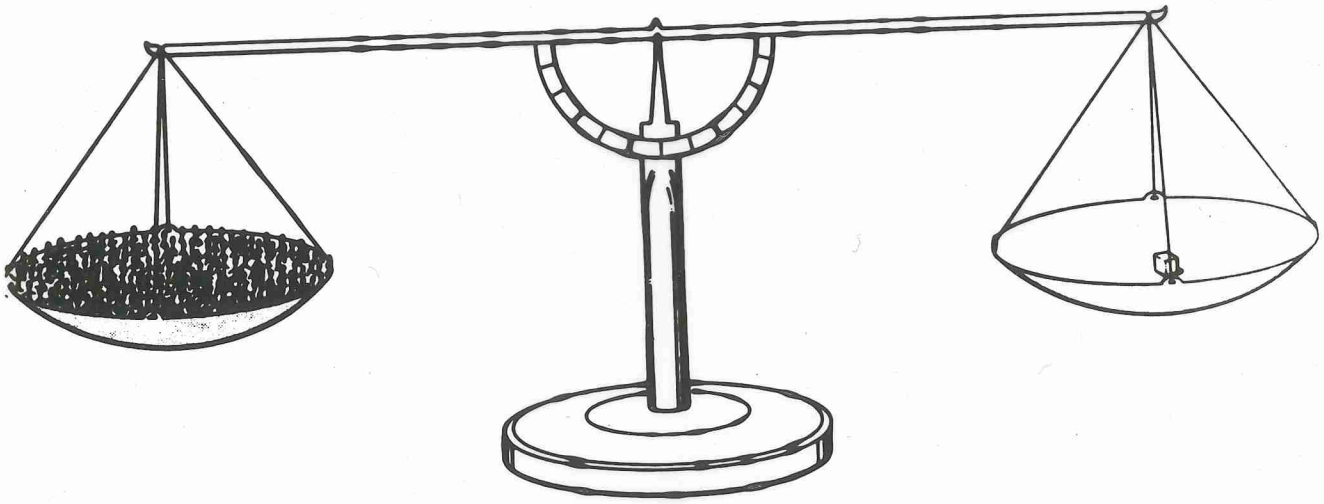


Figure 7.2. A sugarcube of neutron star stuff weighs as much as all of humanity.

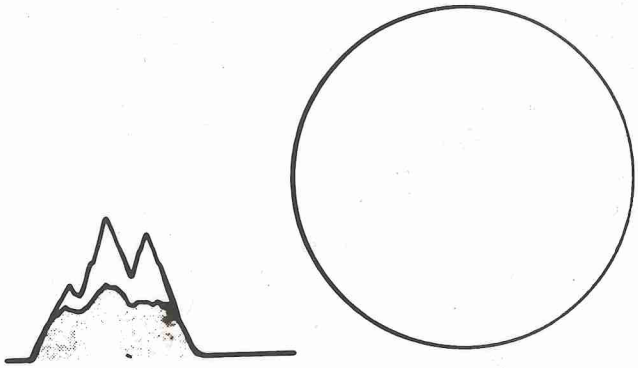


Figure 7.3. A neutron star is only somewhat larger than Mount Everest.

DENSE 10^{14} gm/cm^3

ESCAPE VELOCITY $\sim \frac{1}{2}$ SPEED OF LIGHT

MILLISECOND PULSARS

- (NORMAL) PULSARS BORN SPINNING RAPIDLY (~ 1/10 SEC)
- LOSE ENERGY, SPIN MORE SLOWLY, CEASE TO 'PULSE' WHEN SPINNING AT ~ 10 SEC
- IF IN BINARY SYSTEM, MAY GAIN MASS FROM COMPANION & SPIN-UP TO ~ FEW MILLISEC AND RESUME 'PULSING'.
- ENTER BLACK WIDOW: NEUTRON STAR HEATS/EVAPORATES COMPANION → SINGLE mSEC PULSAR

BLACK HOLES

- STELLAR BHs : endpoints of evolution of massive stars

- GALACTIC BHs : in central regions of many (all ?) galaxies

$$m_* \sim \text{few } m_\odot$$

$$m_{GAL} \sim 10^6 \, m_\odot$$

- OTHERS ? primordial BHs of v. low mass (few ounces) - HAWKING.

NOT MYSTERIOUS - not completely so -

FOLLOW FROM EINSTEIN'S THEORY GENERAL RELATIVITY.

EINSTEIN'S SPECIAL RELATIVITY

SEE OS 5-3

- THE PRINCIPLES OF RELATIVITY
  - LAWS OF PHYSICS SAME FOR ALL OBSERVERS MOVING AT CONSTANT VELOCITY
  - VELOCITY OF LIGHT SAME FOR ALL OBSERVERS

- PREDICTIONS THOROUGHLY TESTED
  - $E = m_0 c^2$
  - MASS INCREASES WITH VELOCITY (Fig 5-18)
  - CLOCKS SLOWED " "
  - LENGTHS SHORTENED

FOR A SERIES OF
INTERESTING ARTICLES
ON GENERAL RELATIVITY

SEE

SCIENCE NEWS

FOR OCT 15, 2015

EINSTEIN'S GENERAL THEORY OF RELATIVITY replaces NEWTON'S VIEW OF GRAVITY

NEWTON

- FORCE TRANSMITTED INSTANTANEOUSLY BETWEEN m AND M
- FORCE → ACCELERATION
- $F = G \frac{mM}{d^2}$

EINSTEIN

- MATTER DISTORTS SPACETIME
- OBJECTS FOLLOW STRAIGHTEST PATH POSSIBLE:

  PATH IS CURVED IN DISTORTED SPACE TIME. OBJECT IS ACCELERATED AS THOUGH FORCE IS ACTING ON IT.

"SPACE TELLS MATTER HOW TO MOVE; MATTER TELLS SPACE HOW TO CURVE." J. A. WHEELER

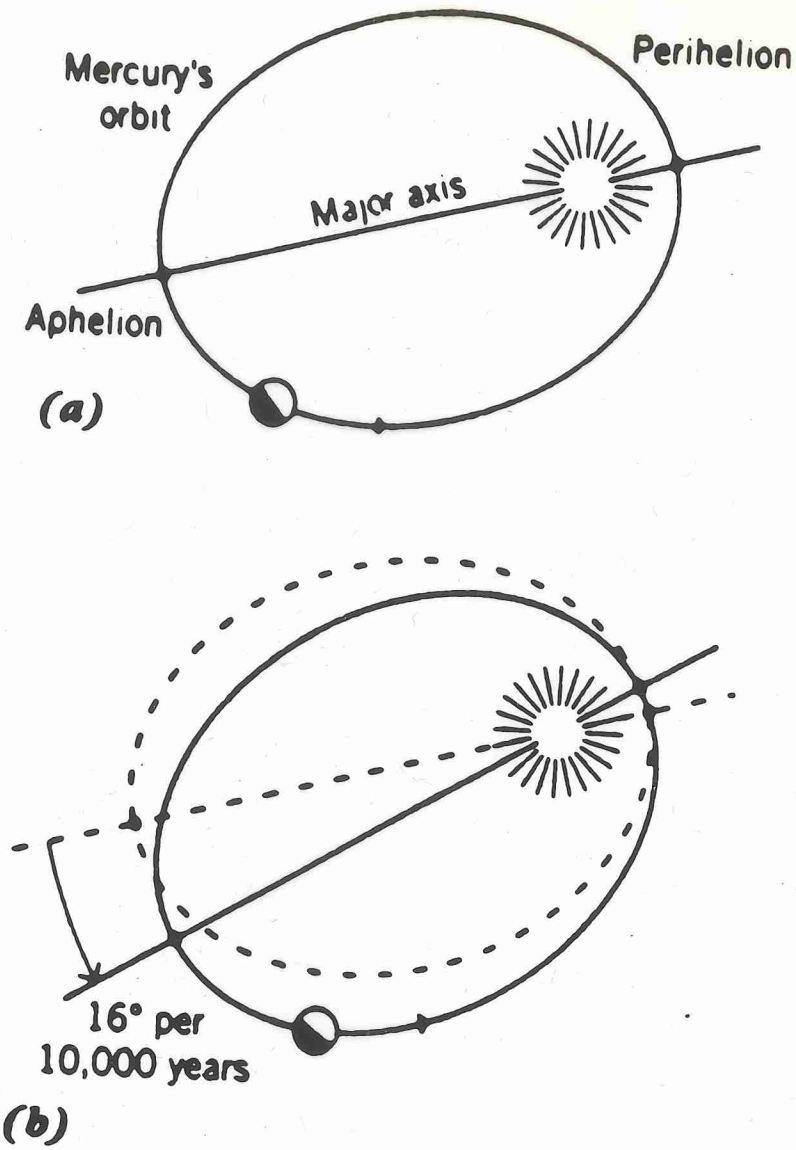


FIGURE 7.11 Perihelion advance of Mercury's orbit. The major axis of the orbit (*a*) rotates in space with respect to the stars (*b*), covering an angle of about 16° every 10,000 years.

TESTS OF GENERAL RELATIVITY

- MERCURY'S ORBIT
  - PERIHELION ADVANCE

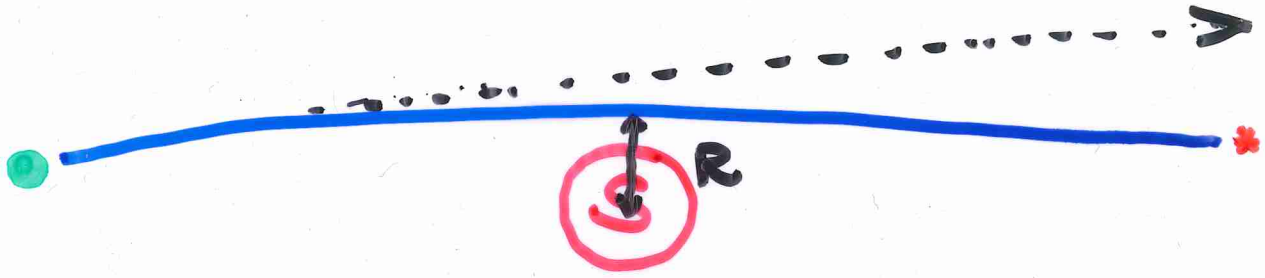
expected by NEWTONIAN gravity but at less than observed rate.

SOURCE	RATE (" /century)
VENUS	277
JUPITER	153
EARTH	90
MARS etc.	11
	531
OBSERVED	574
DIFFERENCE	43

VULCAN?

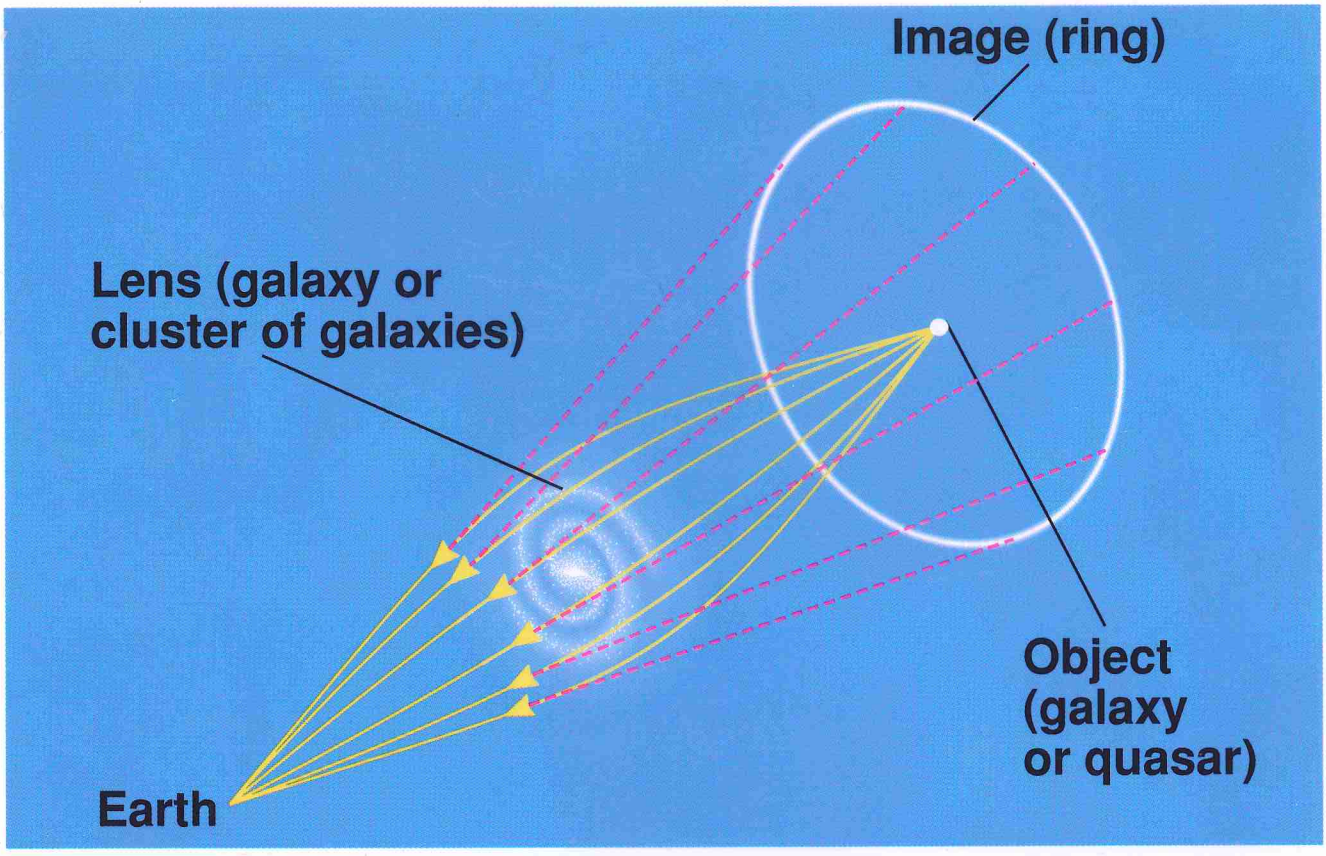
GEN. RELATIVITY?

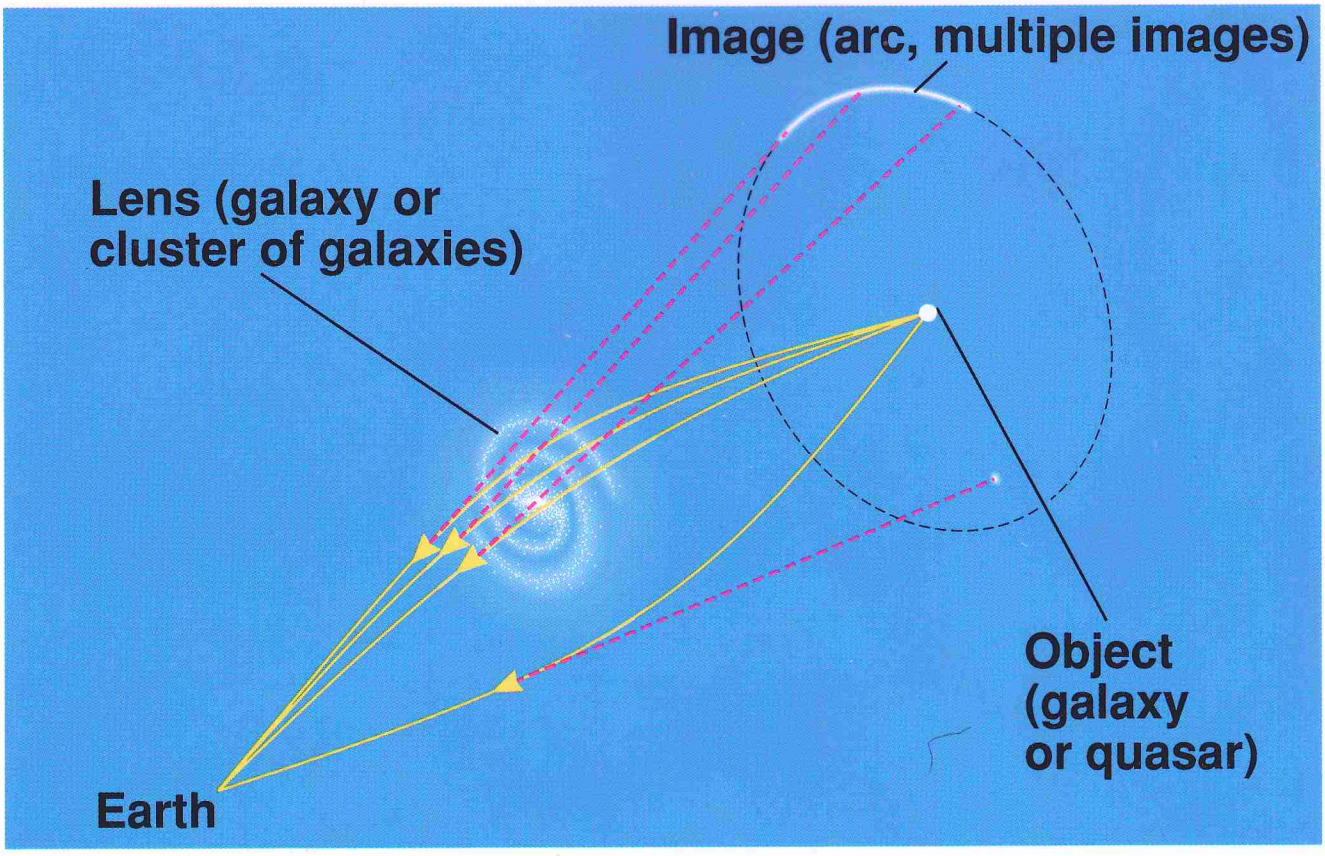
- BENDING OF STARLIGHT / GRAVITATIONAL LENSES
  - STARS AT TOTAL SOLAR ECLIPSE



SHIFT OF POSITION ONLY $\approx 2'' / R(\text{in } R_\odot)$

- ECLIPSES (~10% test)
- SPACECRAFT & RADIO SOURCES (~1% or better)





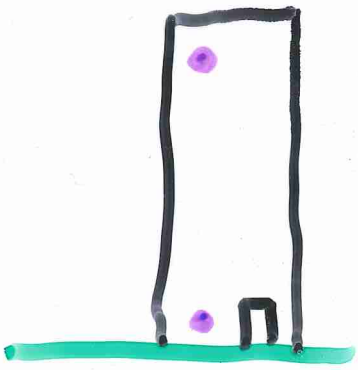
Gravitational lensing geometries

Hartmann/Impey: The Cosmic Journey, 5th ed., Fig. 25-17

GRAVITATIONAL REDSHIFT

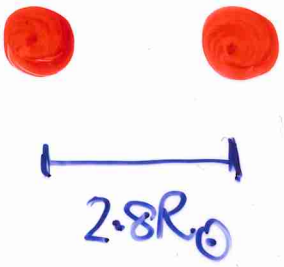
- WAVELENGTHS LENGTHENED IN GRAVITATIONAL FIELD

- TERRESTRIAL TESTS



- STARS, esp. WHITE DWARFS

BINARY PULSAR proof of existence of GRAVITATIONAL WAVES



TWO NEUTRON STARS

- ONE PULSAR 0.059 SEC
- ORBITAL PERIOD 7.75 HRS

(AV. ORBITAL VEL'Y = 0.1 c)

ORBIT DECAYS AS GRAV. WAVES TAKE AWAY ENERGY AND NEUTRON STARS SPIRAL CLOSER, ORBITAL PERIOD SHORTENS THIS IS OBSERVED

STELLAR BLACK HOLES

$m \gtrsim 3M_\odot$ AND NO FUEL REMAINING

IF $<3M_\odot$, OBJECT MAY BE A NEUTRON STAR, $<1.4M_\odot$ MAY BE A WHITE DWARF

— NOTHING OPPOSES CONTINUED COLLAPSE

— NO LIGHT CAN ESCAPE IF RADIUS LESS THAN SCHWARZSCHILD RADIUS

= 3 km for $1M_\odot$

SCHWARZSCHILD RADIUS

$$R_S = 3 \frac{m}{M_{SUN}} \quad \text{in km}$$

$R < R_S$: NO LIGHT CAN ESCAPE

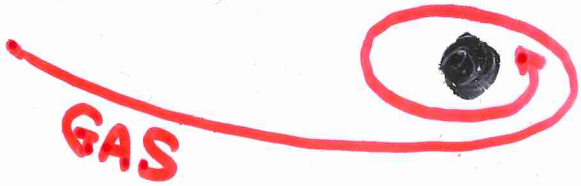
VERY SMALL BLACK HOLES

emit RADIATION

IF NO LIGHT CAN ESCAPE, HOW ARE BH's DETECTED?

- DETECT LIGHT FROM IMMEDIATE VICINITY OF BHs
- INFER $m \gg 3 M_\odot$ FOR OBJECT INSIDE

- GAS 'FALLING' INTO BH (or NS or WD) GAINS KINETIC ENERGY FROM GRAVITATIONAL POTENTIAL ENERGY.
- GAS ATOMS DO NOT FALL DIRECTLY INTO BH (or NS or WD) BUT COLLIDE WITH OTHER ATOMS: KE ⇒ HEAT → EXCITATION OF ATOMS. AND FORMS ACCRETION DISK.
- ACCRETION DISK

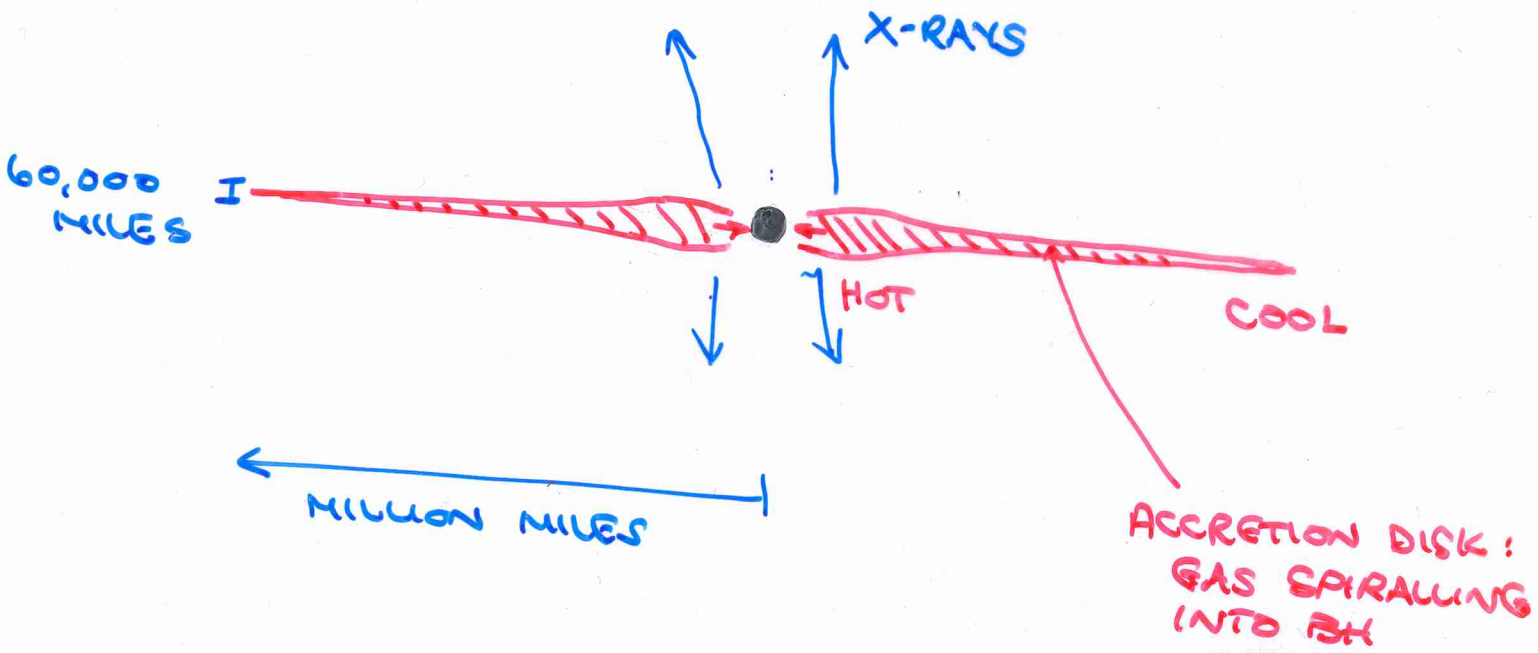


DETECTING BLACK HOLES — ACCRETION & HEATING OF GAS

- ACCRETION FROM STELLAR WIND

- O, B STARS HAVE STRONG STELLAR WINDS DRIVEN BY RADIATION PRESSURE
- PART OF THE WIND IS CAPTURED BY BLACK HOLE (CORE OF FORMER & MORE MASSIVE COMPANION)
- ACCRETION DISK IS HOT, ESPECIALLY IN INNER PART, EMITS X-RAYS. X-RAY SOURCE MAY BE ECLIPSED.

SIDE-VIEW OF ACCRETION DISC



- IS 'UNSEEN' OBJECT A BLACK HOLE?

ACCRETION DISKS FORM AROUND WHITE DWARFS, NEUTRON STARS, BLACK HOLES

NEED ACCURATE ESTIMATE OF SECONDARY'S MASS

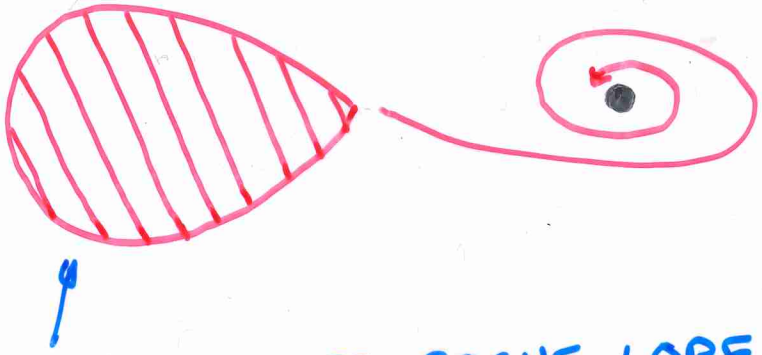
$m < 1.4\ M_\odot$ WHITE DWARF (probably)

$< 2\text{-}3\ M_\odot$ NEUTRON STAR (probably)

$> 2\text{-}3\ M_\odot$ BLACK HOLE (certainly)

MASSES FROM ANALYSIS OF BINARY STARS (* + BH/NS/WD) UNCERTAINTY ARISES FROM ANGLE OF INCLINATION.

- ACCRETION VIA ROCHE LOBE OVERFLOW



STAR FILLS ITS ROCHE LOBE — MASS FLOWS INTO SIMILAR LOBE AROUND COMPACT COMPANION - FORMS ACCRETION DISK

→ X-RAYS

BLACK HOLE CANDIDATES

- **BINARY**

  HMXB — OB STAR WIND → ACCRETION DISC.

  LMXB — ROCHE LOBE OVERFLOW FROM LOW MASS (MS?) STAR → ACCRETION DISC.

- **X-RAY SOURCE**

  RAPID FLICKERING → SMALL SOURCE

  COMPANION UNLIKELY TO BE X-RAY SOURCE

  (ECLIPSES OF X-RAY SOURCE)

- **MASS** $> 3M_\odot$

  $< 3M_\odot$ NS or WD

SEVERAL EXCELLENT BH CANDIDATES NOW KNOWN.

CYGNUS X-1	HMXB	5.6 d	10-15 $M_\odot$
V616 Mon	LMXB	7.8 hrs	3.3-4.2 $M_\odot$
QZ Vul	LMXB	8 hr	5-14 $M_\odot$