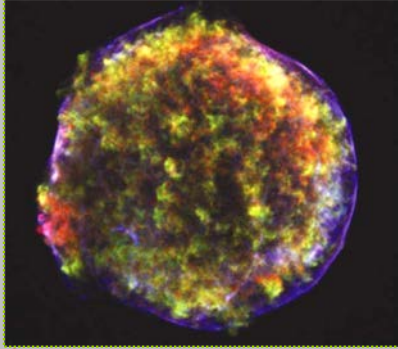


**ASTR 1040: Stars & Galaxies**



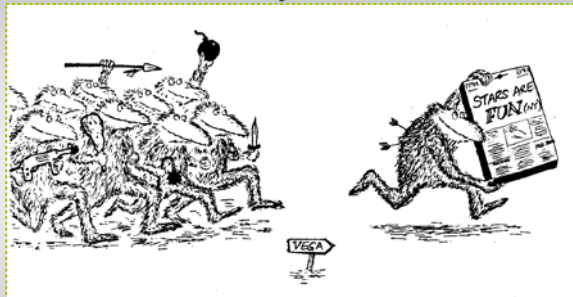
Tycho Brahe SNR (1572)

Prof. Juri Toomre TAs: Ryan Horton, Loren Matilsky  
Lecture 19 Tues 30 Oct 2018  
[zeus.colorado.edu/astr1040-toomre](http://zeus.colorado.edu/astr1040-toomre)

**Joys of Black Holes**

- **Black holes**, their general properties, and their “**care and feeding**” – and **Mr. Einstein’s work** S.2 (special relativity), S.3 (general relativity)
- How to **detect black holes** (indirectly) in close binary systems (read 18.3)
- Best “stellar-mass” black hole candidates: Cygnus X-1, SS433
- **Gamma-ray bursts** (hypernova?)
- **Next: Our Milky Way Galaxy** in overview, aspects of any **spiral galaxy**
- **Overview read Chap 19 “Our Galaxy”**
- No Observatory Night #8 tonight: snow

**So did we really love this exam?**



**RESULTS FROM SECOND MID-TERM EXAM**

**SECOND MID-TERM EXAM**

- **Grade boundaries**, based on 110 points (graded on a “curve”):
- If 98/110 (89%) or over, **A’s** [36%]
- 88/110 (80%) or over, **B’s** [43%]
- 69/110 (63%) or over, **C’s** [21%]

Also +, plain, and – within these ranges

Go through answer sheet – and talk to us if do not understand our choices. Keep exam + answers for future review (comp final)

**SNR “numbers game”**

**SUPERNOVA REMNANTS (SNR) REVISIT**

... EXPANDING DEBRIS OF EXPLOSION  
DO NOT LAST VERY LONG BEFORE DISSIPATING

- FOR ABOUT 3000 YEARS, SEEN IN X-RAY, VISIBLE, RADIO
- AFTER ~ 50,000 YRS, SHOCK WAVE SHOWS PLANE MATERIAL AWAY, BUT GAS HAS COOLED → RADIO EMISSION ALONE
- PROBABLY INVISIBLE AFTER ~ MILLION YEARS

BUT ... SUPERHELLES CAUSED BY SUCCESSIVE SN IN THE ADJACENTLY MAY LAST MUCH LONGER!

THE NUMBERS GAME =

- ~ 120 SNR DETECTED IN OUR GALAXY (MOSTLY IN RADIO)
- 5 HAVE IDENTIFIABLE PULSARS
- ~ 50 SNR IN LMC
- ~ 10 SNR IN SMC

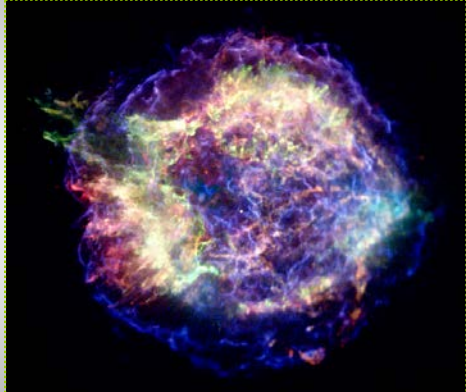
BUT ~ 400 PULSARS FOUND IN OUR GALAXY, ± IN LMC

ANSWER: PULSARS BEING LONGER (~ 4 MY), PROBE MOTION OF PULSAR MAY CAREY IF AWAY FROM SUR



Cygnus Loop

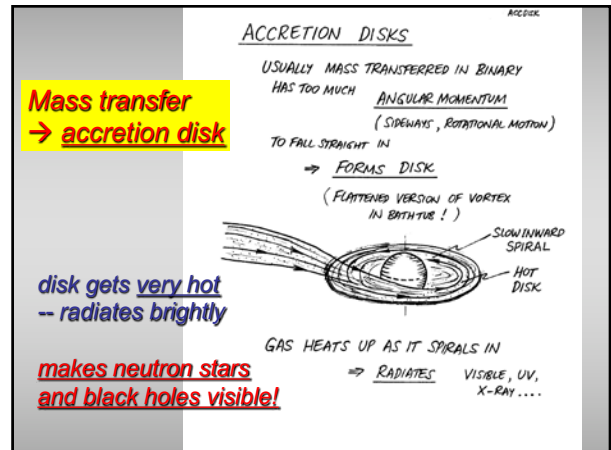
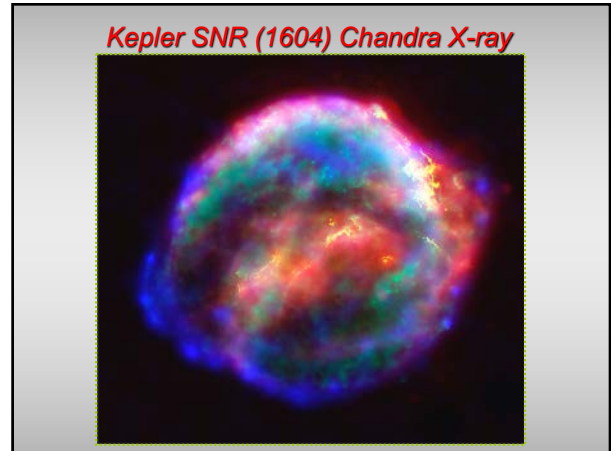
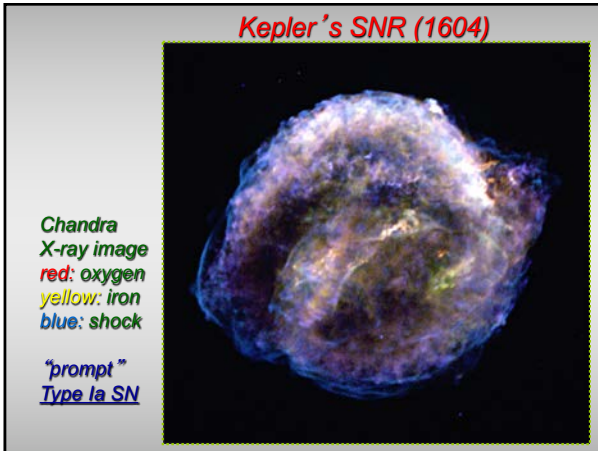
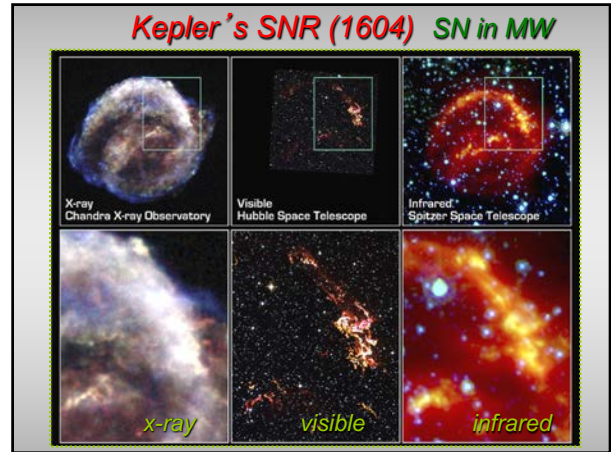
**Cassiopeia A: SN in ~1680 (Flamsteed)**



**REVISIT**

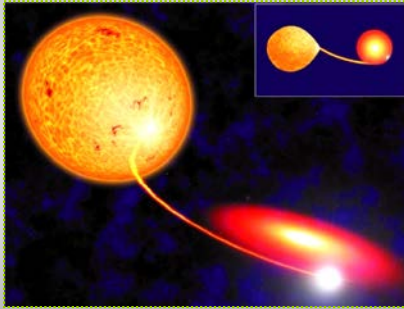
Youngest SNR in MW (Chandra X-ray image) synchrotron emission

Neutron star at center



**"Compact Companions" in Binary Systems**

- Again: **mass transfer** from red giant companion spirals onto accretion disk
- Inner parts become **VERY hot** -- glow in UV, X-rays

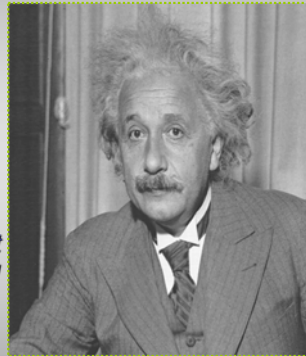


**Reading ahead Clicker – Black Holes**

- What do we mean by the **event horizon** of a black hole? **C.**
- **A.** The distance from black hole at which stable orbits are possible
- **B.** The very center of the black hole
- **C.** The sphere inward from which neither light nor anything else can escape
- **D.** The place where x-rays are emitted

**GR and Spacetime**

- **Einstein's (1911) General Theory of Relativity:** gravity is really the warping of spacetime around an object with much mass
- Light travels in "straight lines" – and its bending comes from **spacetime** being curved by gravity



**Time slowed down ... by moving fast or strong gravity**

Einstein's Special / General Theories of RELATIVITY

Our sense of time is relative ..

**IF nothing can move faster than speed of light, space and time are linked → spacetime**

TIME DILATION .... MEASUREMENTS OF TIME ARE RELATIVE

TIME RUNS SLOWER FOR:

1. FAST MOVING OBJECTS

EINSTEIN 1905 (SPECIAL THEORY OF RELATIVITY)

**"SR"**  
**1905**

ASTRONAUTS (16 km/sec)

TIME SLOWS DOWN  $\sim \frac{1}{10^9} \sim 10^{-9}$  sec/year (AFTER MORE SLOWLY AS VIEWED BY US)

RADIOACTIVE PARTICLE IN ACCELERATOR

MOVING ALMOST AT SPEED OF LIGHT C LIVES 100 - 1000 TIMES LONGER AS VIEWED BY US

2. OBJECTS IN STRONG GRAVITY

EINSTEIN 1911 (GENERAL THEORY OF RELATIVITY)

**"GR"**  
**1911**

ON EARTH: TIME SLOWS DOWN BY

1 PART IN 10 BILLION

WHITE DWARF: 1 PART IN 1000

NEUTRON STAR: TIME IS 70% SLOWER

BLACK HOLE: TIME STOPS

→ TIME APPEARS TO SLOW DOWN IF YOU OBSERVE OBJECT DEEP IN A GRAVITATIONAL FIELD!

**Effects of strong gravity on light**

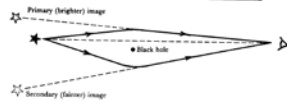
can act like lens

can redshift light

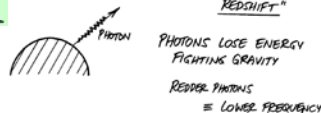
**EFFECTS OF GRAVITY ON LIGHT**

... COURTESY OF EINSTEIN

1. STRONG GRAVITY CAN BEND LIGHT: USUALLY SLIGHT DEFLECTION, BUT IF VERY STRONG GRAVITY → GRAVITATIONAL LENSES!



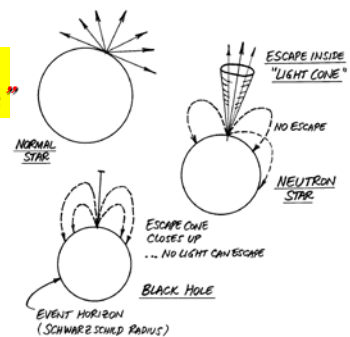
2. LIGHT ESCAPING STRONG GRAVITY FIELD IS REDSHIFTED: "GRAVITATIONAL REDSHIFT"



**Light and "escape cones"**

cone narrows as gravity forces get more intense

**ESCAPE OF LIGHT FROM AN OBJECT**



BLACK HOLE: GRAVITY FORCES SO STRONG NEAR "MASS SINGULARITY" THAT PHOTONS CANNOT ESCAPE!

## Black Holes

- **Escape velocity**  $v_{esc}^2 = 2 \times G \times \text{mass} / R$  (sec 4.5)
- **Mitchell & Laplace in 1700's** (post Newton) speculated about **objects so compact that  $v_{esc}$  exceeds speed of light**
- **Einstein** showed space and time are not distinct (IF speed of light  $c$  is constant) → **SPACETIME singularity in spacetime → black hole**

## "Event horizon"

... SCHWARZSCHILD RADIUS FOR BLACK HOLES

**Schwarzschild radius:** where escape velocity is speed of light

$R_s = 2G \text{ mass} / c^2$

most simply:  
( $R_s$  in km,  
 $R_s = 3 M$   
 $M$  in  $M_{sun}$ )

SOME SCHWARZSCHILD RADIUS:

	SCHWARZSCHILD RADIUS	BLACK-HOLE RADIUS
EARTH MASS	$3 \times 10^{-4} M_{\odot}$	0.9 cm!
SUN	$M_{\odot}$	3 km
GALAXY	$10^{11} M_{\odot}$	0.05 LIGHT YEAR

BUT PROBLEM IS HOW TO STUFF SO MUCH MASS INTO SUCH A SMALL VOLUME!

## "BLACK HOLES HAVE NO HAIR"

ALL BLACK HOLES DESCRIBED BY JUST 3 NUMBERS

... THEIR TOTAL: MASS  
ELECTRIC CHARGE  
ANGULAR MOMENTUM

NO FURTHER STRUCTURE, OR "HAIR"!

**EVENT HORIZON** (SCHWARZSCHILD RADIUS)  
 $R_s = 2G \text{ MASS} / c^2$

SPINNING BLACK HOLE DRAGS NEARBY SPACETIME WITH IT  
→ **ERGOSPHERE**: ROTATING ZONE OF SPACE JUST OUTSIDE EVENT HORIZON

FLY THROUGH ERGOSPHERE CAN WITHOUT TRAVELLING BACK INTO SPACE WITH ADDITIONAL "GAIN"  
... CAN EXTRACT ENERGY FROM HOLE'S ROTATION!

**Ergosphere: spinning BH drags nearby spacetime along**

## Warping of Space by Gravity

- **Gravity imposes curvature on space**
  - light's path through space will be "bent by gravity"
  - within the event horizon, it cannot climb out of the hole
- **As matter approaches event horizon...**
  - tidal forces are tremendous
  - object would be "spaghettified"

## 3 aspects of falling into a black hole:

### 1) Spaghettified

- **As matter approaches the singularity...**
  - tidal forces (difference between gravitational force at two points) are tremendous
  - Your feet would feel a much stronger pull of gravity than your head
  - object would be "spaghettified"

## Three aspects of falling into a black hole:

### 2) Gravitational Redshift

**From mothership's view**

- As the probe gets closer and closer to the event horizon, the light becomes more and more **redshifted**
  - Photons lose energy climbing out of the black hole gravity well
  - At the EH (from our view), photons are redshifted out of existence (zero energy)

**From probe's view:**

- Outside world gets **blueshifted**
  - Photons gain energy falling into the black hole gravity well

### Three aspects of falling into a black hole:

## 3) Time Dilation

**From mothership's view**

- As the probe gets closer and closer to the event horizon, its clock *appears to slow down*
- The probe (and clock) never get to the event horizon
  - It moves slower and slower, eventually freezing at the EH



**From probe's view:**

- it heads straight into the black hole
  - Nothing special at the event horizon
- Outside world clock appears to be sped up

25

## Black Holes Don't SUCK!

- Black holes have gravity, just like "normal" stars, planets etc.
- The only problem is that you can get SO close to the concentrated gravity near a black hole that you can't get out again

### HOW TO "DETECT" A BLACK HOLE ?

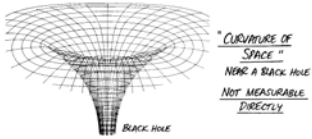
( VERY CAREFULLY ! )

... ONLY THROUGH EFFECTS ON NEARBY MATTER

MOSTLY LOOK AT CLOSE BINARIES AND SEARCH FOR CONTACT X-RAY SOURCES

**CRITERIA :**

1. "INVISIBLE" STAR IN BINARY SYSTEM IS TOO MASSIVE TO BE WHITE DWARF OR NEUTRON STAR  $\Rightarrow$  MASS  $\geq 3 M_{\odot}$
2. TOO SMALL IN RADIUS TO BE DETECTABLE AS A NORMAL STAR



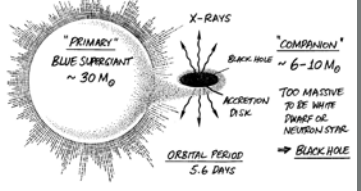
**How to "detect" a black hole**

### OBSERVING A BLACK HOLE:


## Cygnus X-1

CYGNUS X-1 :  
MOST VIABLE BLACK-HOLE CANDIDATE

- ECLIPSING BINARY SYSTEM IN SN REMNANT (CYGNUS LOOP)
- STRONG X-RAY SOURCE , VERY RAPID FLUCTUATIONS
- DOPPLER VELOCITY VARIATIONS OF PRIMARY INDICATE MASSIVE COMPANION (NOT SEEN DIRECTLY)



- STELLAR WIND POURS MATTER ONTO HUGE ACCRETION DISK
- INFALLING GAS HEATED AS SPIRALS INWARD, GETS SO HOT THAT EMITS X-RAYS AT INNER EDGE OF DISK




### Cygnus X-1: Blue supergiant (strong winds) pours H + He onto accretion disk of black hole



**Views of "Veil Nebula"**



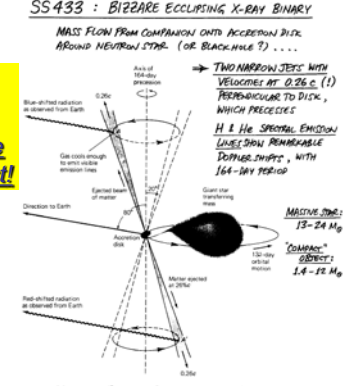
Such SNR may have a BH lurking!  
.. but not this one

**SS 433 : BIZARRE ECLIPSING X-RAY BINARY**

MASS FLOW FROM COMPANION ONTO ACCRETION DISK AROUND NEUTRON STAR (OR BLACK HOLE?) ...

**SS 433**  
top candidate for wild object!

another stellar-size black hole



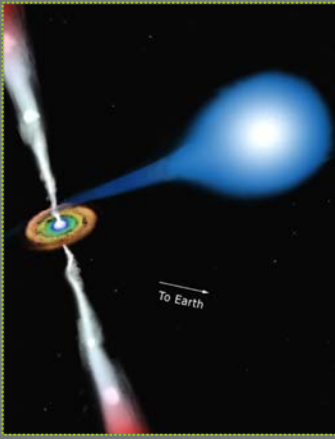
→ TWO NARROW JETS WITH VELOCITIES AT 0.26 c (1) PERPENDICULAR TO DISK, WHICH PRECEDES

H & He SPECTRAL EMISSION LINE SHOWN REMARKABLE DOPPLER SHIFTS, WITH 164-DAY PERIOD

MASSIVE STAR: 13-24  $M_{\odot}$

"COMPACT" OBJECT: 1.4-2.2  $M_{\odot}$

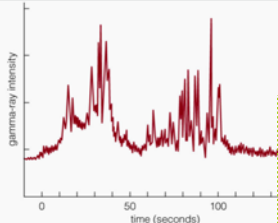
IS MASS TRANSFER SO STRONG ONTO ACCRETION DISK THAT ONLY WAY OUT IS ALONG ROTATION AXIS?



**SS 443**  
BH + jets

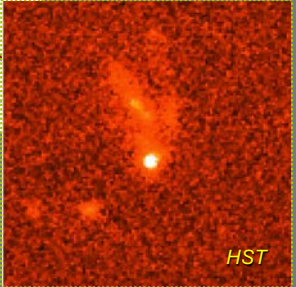
**Gamma-Ray Bursts**

**HYPERNOVA ?**  
Collapse of very massive star > BH



Luminosity ~  $10^6$  to  $10^9$  times output from galaxy

Visible from across the universe !



HST

**Review Clicker – Size of Black Hole**

- What does the **Schwarzschild radius** of a black hole (BH) depend on? **C.**
- **A.** Both mass and chemical composition of the BH
- **B.** Radius of BH, as measured by careful observations of its size
- **C.** Only the mass of BH
- **D.** Whether BH formed in massive star supernova or in some other way