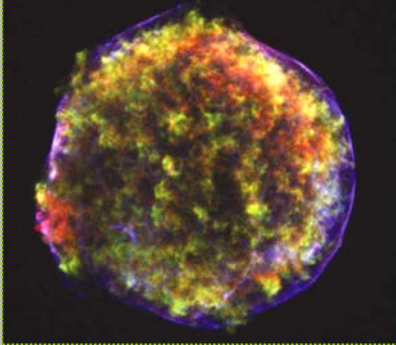


ASTR 1040: Stars & Galaxies



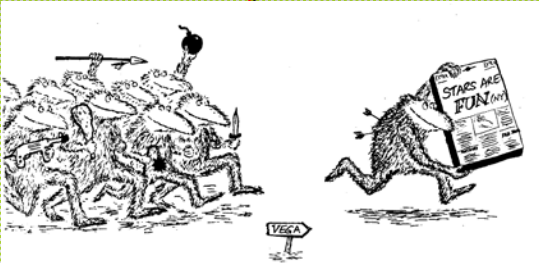
Tycho Brahe SNR (1572)

Prof. Juri Toomre TAs: Daniel Segal, Max Weiner
Lecture 19 Tues 17 Mar 2020
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”**
- **Update on observatory projects**

So did we really love this exam?



RESULTS FROM SECOND MID-TERM EXAM

E-mail Juri with “competitive crib sheet” entries (pdf file)

SECOND MID-TERM EXAM

- **Grade boundaries**, based on 110 points (graded on a “curve”):
- If 98/110 (89%) or over, **A’s [42%]**
- 80/110 (73%) or over, **B’s [42%]**
- 66/110 (60%) or over, **C’s [14%]**

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)**

How we will be zoom-interactive

- “**Raise Hand**” (Max monitors “Participants”)
- “**Send Chat**” Message (Max will act)
- In both cases, Juri will get to your question or comment within at most a few minutes
- Or if pressing, Unmute your mike and ask question
- We can adjust “how to interact”, with your advice and experience

SNR “numbers game”

SUPERNOVA REMNANTS (SNR) REVISIT

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

- FOR ABOUT 5000 YEARS, SEEN IN X-RAY, VISIBLE, RADIO
- AFTER ~50,000 YEARS, SHOCK WAVE SHOWS SOME MATERIAL AHEAD, BUT GAS HAS COOLED → RADIO EMISSION ABANDONED
- PROBABLY INVISIBLE AFTER ~ MILLION YEARS

BUT... SUPERHELIXES CAUSED BY SUCCESSIVE SN IN OR ASSOCIATION MAY LAST MUCH LONGER!

THE NUMBERS GAME:

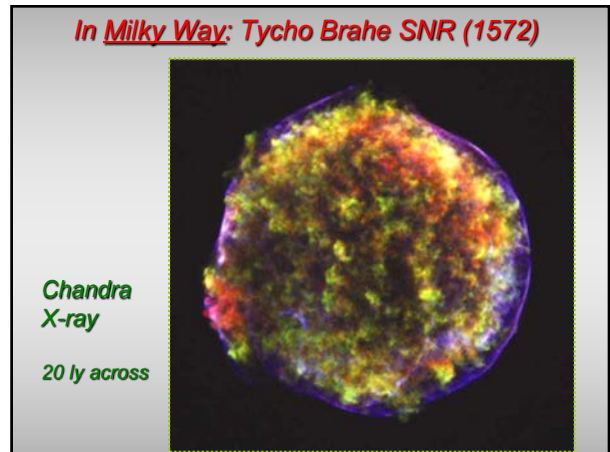
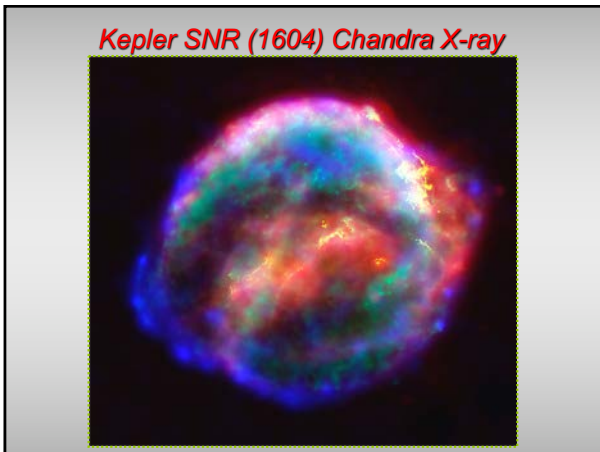
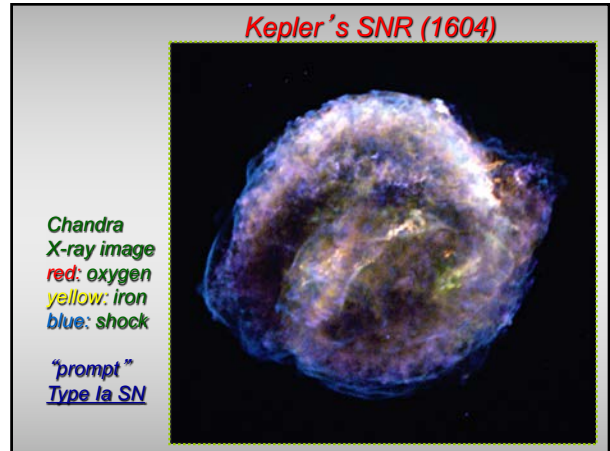
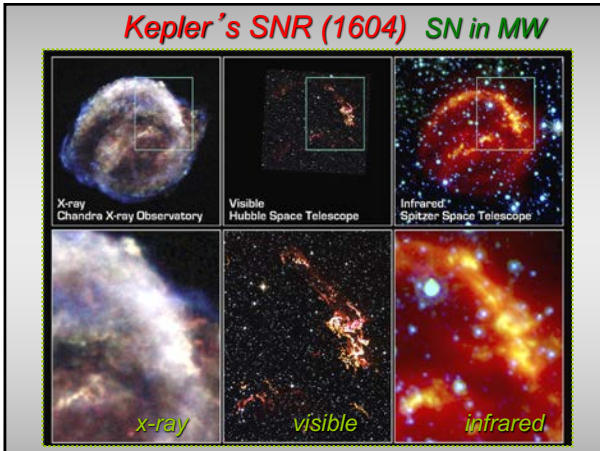
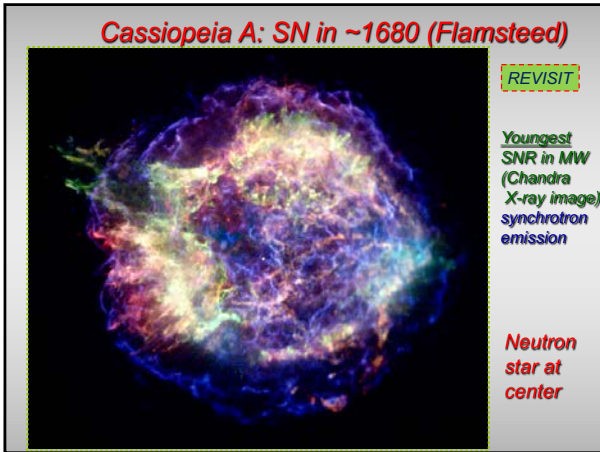
- ~120 SNR DETECTED IN OUR GALAXY (MOSTLY IN RADIO)
- 5 HAVE IDENTIFIABLE PULSARS
- ~50 SNR IN LMC
- ~10 SNR IN SMC

BUT ~400 PULSARS FOUND IN OUR GALAXY, 1 IN LMC

ANSWER: PULSARS VISIBLE LONGER (~4 MY), PROBABLY METHOD OF PULSAR MAY CARRY IT AWAY FROM SNR



Cygnus Loop



Questions or Comments

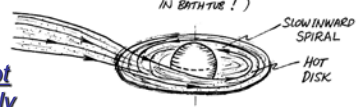
Then we use Break-out Rooms for ~7 minutes to exchange impressions of "how are things"

ACCELIK

ACCRETION DISKS

USUALLY MASS TRANSFERRED IN BINARY HAS TOO MUCH ANGULAR MOMENTUM (SIDEWAYS, ROTATIONAL MOTION) TO FALL STRAIGHT IN

⇒ FORMS DISK
(FLATTENED VERSION OF VORTEX IN BATHTUB !)



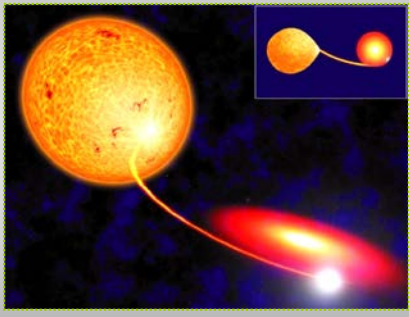
disk gets very hot – radiates brightly

makes neutron stars and black holes visible!

GAS HEATS UP AS IT SPIRALS IN ⇒ RADIATES VISIBLE, UV, X-RAY

“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

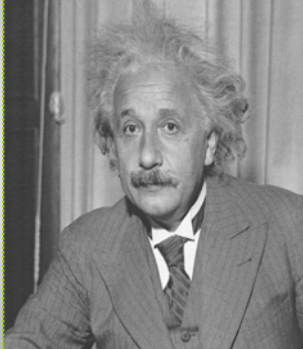


Reading ahead – Black Holes

- 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)
 - ASTRONAUTS (16 km/sec)
 - TIME SLOWS DOWN $\sim \frac{1}{10^9} \sim 10^{-9}$ sec/week (AFTER MORE SLOWLY AS VIEWED BY US)
 - RADIOACTIVE PARTICLES 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)
 - ON EARTH: TIME SLOWS DOWN BY 1 PART IN 50 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 PROCESS DEEP IN A GRAVITATIONAL FIELD!

EFFECTS OF GRAVITY ON LIGHT
... COURTESY OF EINSTEIN

Effects of strong gravity on light

can act like lens

can redshift light

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

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

PHOTONS LOSE ENERGY FIGHTING GRAVITY
REDDER PHOTONS \equiv LOWER FREQUENCY

ESCAPE OF LIGHT FROM AN OBJECT

Light and "escape cones"

cone narrows as gravity forces get more intense

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

Questions or Comments

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) \rightarrow **SPACETIME singularity in spacetime \rightarrow black hole**

"Event horizon"

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})

"EVENT HORIZON"
... SCHWARZSCHILD RADIUS FOR BLACK HOLES

SOME SCHWARZSCHILD RADIUS:

	BLACK-HOLE RADIUS
EARTH MASS $3 \times 10^{-6} M_{\odot}$	0.9 cm!
SUN M_{\odot}	3 km
GALAXY $10^{11} M_{\odot}$	0.03 LIGHT YEAR

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

"Black holes have no hair"

Only three numbers describe BH!

Ergosphere: drags nearby spacetime along

"BLACK HOLES HAVE NO HAIR"
ALL BLACK HOLES DESCRIBED BY JUST 3 NUMBERS:
... THEIR TOTAL: MASS
ELECTRIC CHARGE
ANGULAR MOMENTUM
NO PARTIAL STRUCTURE, OR "HAIR"!

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

SPINNING BLACK HOLES DRAG NEARBY SPACETIME WITH IT
 \Rightarrow **ERGOSPHERE:** ROTATING ZONE OF SPACE JUST OUTSIDE EVENT HORIZON

FLYBY THROUGH ERGOSPHERE CAN CATASTROPHICALLY TRAVELLER BACK INTO SPACE WITH ADDED "ENERGY"
... CAN EXTRACT ENERGY FROM HOLE'S ROTATION!