The Most Massive Known Stellar-Mass Black Hole

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UC Berkeley 2/7/2008
The Fattest Dance Partner in the Known Universe?

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Cast of Characters: IC 10, the galaxy

- Discovered: 1889
- Constellation: Cassiopeia
- Apparent Dimensions: 6′.8×5′.9
- Distance: 2.2 Mly (660 kpc)
- Redshift: z = -0.001161
- Type: Irregular starburst
- Metallicity: lower than MW, higher than SMC
- Lots of star formation!!!

Image courtesy of Adam Block/NOAO/AURA/NSF.
REVIEW: Black Holes (BHs)

- Massive, compact objects with so much gravitational pull that not even light can escape.
- Super-massive BHs:
  - Found in the centers of galaxies and galaxy clusters.
  - Billions of $M_\odot$.
- Stellar-mass BHs:
  - Found in galaxies where massive stars were born.
  - Stars born with $>20M_\odot$ will explode as type II supernovae after a few million years and leave behind a BH.
  - 1.5 – 10 $M_\odot$.
- Can’t observe BHs directly.
- Can observe hot, high energy X-rays coming from a disk of infalling material around the BH (an “accretion disk”).
Cast of Characters: IC 10 X-1, the BH

- Bright X-ray source in IC 10.
- Thought to be a BH with an accretion disk.
- Brightness varies regularly with time.
Regular X-ray brightness variability means there should be a binary companion.

The X-rays get dimmer when the companion moves in front of the BH (with accretion disk).

This is an “eclipsing binary” system.

Recall this is similar to the “transit method” of finding extrasolar planets.
Evolved, massive stars (think giants and supergiants).

*Strong, hot, and fast stellar winds.*

Thought to be born with $>20 \, M_\odot$.

Have lots of Helium (but lose most Hydrogen in wind).

Loses $\sim 10^{10}$ times as much mass per year as the Sun.
Cast of Characters: [MAC92] 17A, the WR

- WR star, 17 – 35$M_\odot$, tens of $R_\odot$.
- Optical counterpart to IC 10 X-1.
- Brightness constant with time.
  - This makes sense due to the size difference between the BH and WR.


Image courtesy of HyperPhysics (©C.R. Nave, 2006).
Dance Partners: IC 10 X-1 and [MAC92] 17A

- This is a binary system!!!
- The X-ray eclipse has been seen.
- The BH is too small to show an eclipse in the light of the WR.
- How else can we get info about this binary?

Image courtesy of Aurore Simonnet/Sonoma State University/NASA.
REVIEW: The Doppler Shift

- Motion changes the waves emitted from an object.
  - Train whistles.
  - Ambulance sirens.
  - Light from stars.
- X-rays are hard to measure accurately, so we can’t see the Doppler shift of the BH/accretion disk’s light.
- Optical light is easier to measure, so we should see a Doppler shift in light from the WR.

Image courtesy of Geoff Marcy, UC Berkeley.
Spectra of [MAC92] 17A

- **QUICK REVIEW:**
  A spectrum (pl. spectra) is a plot of the brightness of an object at different wavelengths of light.

- This is a combination of 10 individual spectra of [MAC92] 17A.
The narrow and strong H and O come from gas clouds ("nebulae") in IC 10.
- H\(\beta\) is the n=4 \(\rightarrow\) 2 electron jump.

The broader (and weaker) He comes from the WR.
- This is expected from WR stars.
A Big Telescope for a Big Job

- Used the Keck-I 10 m telescope on Mauna Kea, Hawaii.
- Took 10 spectra of the WR:
  - 3 on Nov. 11, 2007
  - 2 on Nov. 12, 2007
  - 1 on Nov. 13, 2007
  - 3 on Nov. 16, 2007
  - 1 on Dec. 12, 2007

Image courtesy of NASA.
Doppler Shiftin’

- These are three representative spectra of the WR star.
- If we watch the He spectral line closely, we should see it get Doppler shifted back and forth as the WR star and BH orbit each other.
- The amount of shifting can be converted into a velocity of the WR star.
- **WE SEE IT MOVIN’!!!**
Round and Round and Round They Go

- This is the radial-velocity of the WR star versus time.
- The points are the data, the line is a cosine fit.
- Two full orbits are shown.
- The error bars are from the uncertainty in the peak of the He line.
- The data has been “folded”.

[Graph showing radial velocity vs. time and phase]
REVIEW: Kepler’s Third Law

- Kepler figured out that the time it takes to go around the Sun ("period") squared is proportional to the average distance from the Sun ("semi-major axis") cubed.
- Newton showed it came from his Law of Gravity and gave a more general version.
- Since we usually measure a velocity instead of a semi-major axis, we use a related equation called the Mass Function.
From Velocities to a Mass

We can measure $P$ and $K$ from our radial-velocity curve.

- $P = 34.9$ hours
- $K = 370$ km/s

- $f(M) = 7.6 \, M_\odot$
- If we assume a value of $i$ and $m$, we can calculate $M$!
- $i$ is the inclination of the orbit (with respect to our line of sight).
- X-ray eclipses mean $i$ should be near $90^\circ$…
- …but the BH is much smaller than the WR.
- We assumed $45^\circ < i < 90^\circ$, but it’s probably pretty close to $90^\circ$. 
Getting a BH Mass

\[ f(M) \gg 7.6M_\odot \]

- We still need to choose a mass, \( m \), for the WR star in order to get a mass for the BH, \( M \).
- [MAC92] 17A is probably 35\( M_\odot \), but could be as low as 17\( M_\odot \).
- Remember, the inclination is probably about 90°.
Getting a Range of BH Masses

- The minimum mass of the BH is $23M_\odot$.
- The most likely mass of the BH is about $33M_\odot$.
- As the inclination gets smaller, the BH mass get larger.
The New Record Holder???

- Minimum mass: $23M_{\odot}$
- Most likely mass: $33M_{\odot}$
- Most theories predict stellar-mass BHs of $1.5 - 10M_{\odot}$.
- Some computer models get masses up to 12 or $15M_{\odot}$.
- Before Oct. 2007, no one had observed a stellar-mass BH heavier than about $10M_{\odot}$.
- In October, a $16M_{\odot}$ BH was discovered in M33.
- Also in October, a group from Harvard claimed that IC 10 X-1 was a $33M_{\odot}$ BH, but the data that they used was very sketchy.

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**Derived Black Hole Mass ($M_{\odot}$)**

<table>
<thead>
<tr>
<th>Inclination (deg)</th>
<th>Wolf-Rayet Mass ($M_{\odot}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17</td>
</tr>
<tr>
<td>90</td>
<td>$23.1 \pm 2.1$</td>
</tr>
<tr>
<td>60</td>
<td>$29.3 \pm 2.8$</td>
</tr>
<tr>
<td>45</td>
<td>$42.4 \pm 4.4$</td>
</tr>
</tbody>
</table>
The New Record Holder!!!

- We tried to confirm (or disprove) the Harvard group’s result.
- Our data was much better quality and we had many more observations than they did.
- Interestingly enough, they basically got the right answer!!!

“I almost fell out of my chair when I read your abstract....
....didn't really believe our mass estimate! But your radial velocity curve is very convincing.”

--Andrea Prestwich, first author of the Harvard group’s paper, in an email to Prof. Filippenko and I

“Thus, we have shown that IC 10 X-1 is indeed a WR/BH binary containing the most massive known stellar-mass BH.”
The End