Intermediate-Mass Black Holes in the Local Universe

Lessons from G1

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Range of Black Hole Masses $M_{\text{BH}}$

- Stellar mass black holes $M_{\text{BH}} < 40 \, M_\odot$
  - Silverman & Filippenko (2008)
- Massive black holes $M_{\text{BH}} > 10^6 \, M_\odot$
  - Megamasers (Lo 2005)
  - Stellar dynamics
    - Ferrarese & Ford (2005) CfAz
    - Resolve sphere of influence
    - Access $M_{\text{BH}} \sim 10^5 \, M_\odot$ with 30m
- Intermediate-mass black holes (IMBHs)
  - $40 \, M_\odot < M_{\text{BH}} < 10^5 \, M_\odot$
  - Almost no access via stellar dynamics beyond Local Group
  - Hindrance to demographic studies
Importance of Intermediate-Mass Black Holes

- Predictions of gravity wave signals for Laser Interferometer Space Antenna (Bender & Pollack 2003)
- Formation of seed black holes
  - Volonteri et al. (2008), Bellovary et al. (2010)
- Simulations of gravity wave recoil
  - Holley-Bockelmann et al. (2008)
Candidate Intermediate-Mass Black Holes

Globular cluster $\omega$ Cen at distance $d = 5$ kpc

- Most luminous globular cluster in Milky Way
- Stellar dynamics via HST and VLT
  - Noyola et al. (2010)
    - Radial velocities
    - $M_{\text{BH}} \sim 4.7 \times 10^4 M_\odot$
  - Van der Marel & Anderson (2010)
    - Radial velocities and proper motions
    - $M_{\text{BH}} < 1.2 \times 10^4 M_\odot$
    - Origin of differences unclear
Candidate Intermediate-Mass Black Holes
Globular cluster G1 at d = 780 kpc

• Amongst the most luminous globular clusters in M31
• Stellar dynamics via HST and Keck
  – Gebhardt et al. (2002, 2005)
    • Radial velocities
    • \( M_{BH} \sim 1.8 \times 10^4 M_\odot \)
• X-ray counterpart via XMM and Chandra
  – Pooley & Rappaport (2006), Kong et al. (2010)
  – \( L_X \sim 2 \times 10^{36} \) ergs/s
  – Low-mass stellar binary? Viable
  – Accretion onto candidate IMBH? Viable
Candidate Intermediate-Mass Black Holes
Globular cluster G1 at $d = 780$ kpc

- Radio counterpart via NRAO VLA (Ulvestad et al. 2007)
  - Observed flux density $S \sim 30 \, \mu$Jy
  - Stellar binary with $M_{\text{BH}} \sim 10 \, M_\odot$?
    - Not viable: predicted $S$ too low
  - IMBH with $M_{\text{BH}} \sim 1.8 \times 10^4 \, M_\odot$?
    - Viable: predicted $S$ about right
- Planetary wind nebula?
  - Unlikely in an old stellar population but can test via VLBI

\[
S_{5 \text{ GHz}} = 52 \left( \frac{L_X}{10^{36} \text{ ergs s}^{-1}} \right)^{0.6} \left( \frac{M_{\text{BH}}}{10^4 \, M_\odot} \right)^{0.78} \times \left( \frac{d}{600 \, \text{kpc}} \right)^{-2} \, \mu\text{Jy.} \quad \pm \text{factor of 8}
\]
Candidate Intermediate-Mass Black Holes
Globular clusters at d = 4 – 40 Mpc

- 1000s localized via HST
  - Jordan, Humphrey, Masters …
  - Eg, globular clusters in M87
- 100s have X-ray counterparts
  - Kundu, Sarazin, Kim, Sivakoff …
  - Eg, M87 $L_X > 5 \times 10^{38}$ ergs/s
- X-ray sources reside preferentially in the most luminous globular clusters
- Mainly low-mass stellar binaries
- But could some be G1 analogs?
  - $M_{BH} \sim 1.8 \times 10^4 M_\odot$
  
\[ S_{\text{GHz}} = 52 \left( \frac{L_X}{10^{36} \text{ ergs s}^{-1}} \right)^{0.6} \left( \frac{M_{BH}}{10^4 M_\odot} \right)^{0.78} \times \left( \frac{d}{600 \text{ kpc}} \right)^{-2} \mu\text{Jy} \]
Candidate Intermediate-Mass Black Holes
Globular clusters in NGC 4697 at d = 11 Mpc

- Elliptical galaxy studied via HST and Chandra (Sivakoff et al. 2008)
- 34 globular clusters with X-ray counterparts
  - g ~ 19 – 25 mag
  - $L_X > 10^{37}$ ergs/s
- VLA 8.5 GHz (Wrobel et al. 2008)
- Resolution 0.3 arcsec = 16 pc
- G1 g ~ 20 mag
- 18 clusters with g ~ 19 – 22 mag
Candidate Intermediate-Mass Black Holes
Globular clusters in NGC 4697 at d = 11 Mpc

- $M_{\text{BH}} \sim 1.8 \times 10^4 M_\odot$ like G1
- $L_X$ from Chandra
- Predict radio flux density $S$

$$S_{s\text{ GHz}} = 52 \left( \frac{L_X}{10^{36} \text{ ergs s}^{-1}} \right)^{0.6} \left( \frac{M_{\text{BH}}}{10^4 M_\odot} \right)^{0.78} \times \left( \frac{d}{600 \text{ kpc}} \right)^{-2} \mu\text{Jy.}$$

- Predicted $S \sim 1 - 7 \mu\text{Jy}$
- Each $S$ uncertain by $\pm$ factor of 8
- Detections of G1 analogs feasible with NRAO Expanded VLA

Globular Clusters in NGC 4697 with $g \sim 19-22$
- VLA $3\sigma$ upper limits at 8.5 GHz
- EVLA $3\sigma$ sensitivity at 6 GHz in 2012
Summary

Intermediate-mass black holes (IMBHs) have masses $40 \, M_\odot < M_{BH} < 10^5 \, M_\odot$

Demographics key for gravity waves, seed black holes, recoiling black holes

Almost no access via stellar dynamics beyond Local Group, even with 30m

Radio and X-ray properties of G1 consistent with $M_{BH} \sim 1.8 \times 10^4 \, M_\odot$

EVLA detections of G1 analogs beyond Local Group are feasible