BH Astrophys. Ch4
Intermediate Mass Black Holes

Outline

1. The definition

Possible candidates:

2. ULXs (Ultra-luminous X-ray sources) in star-forming galaxies

3. Globular cluster cores in our Milky Way and Andromeda

4. Possible IMBH near the center of the Milky Way

5.Low-luminosity Hard X-ray/radio sources in the galactic bulge and other population II systems

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the definition

Stellar mass BH 5~15$M_\odot$
(popIII stars may form ~50 $M_\odot$ BHs)

SMBHs: 10^5 ~10^{10} $M_\odot$

Intermediate mass black holes M~ 50-10^4 $M_\odot$

Each galaxy may have many IMBHs as isolated objects, in exotic binary systems, as anchors in its star clusters, or even clustered around the central SMBH at the galactic center.

The challenge in this area of black hole research is to determine which of the suggested IMBH candidates, if any, are correct and how important black holes of intermediate mass may be in the evolution of stars, galaxies, and supermassive black holes.

Possible candidates (as of 2011)

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ULXs—Rough estimates

Sources that are as bright as 10^{39} erg/s in X-rays and clearly not SMBHs are called ULXs (Ultra-Luminous X-ray sources)

The practical range is 10^{39} erg/s $< L_X^{ULX/HLX} < 10^{41}$ erg/s (HLX)

↓

Assuming Eddington luminosity, they must be at least 30~3000 $M_\odot$

↓

Assuming more realistic 10-30% Eddington luminosity, mass range would be $10^2 \sim 10^4$ $M_\odot$, right where we expect IMBHs to be.

ULXs—Early observations

1981: Several non-nuclear sources in spiral arm with $L_X > 10^{39}$ erg/s were found.

1990s: ROSAT found that…
1 in every 5 galaxies had a ULX, and
5-10 in each starburst galaxy observed

Single sources ?

Groups?

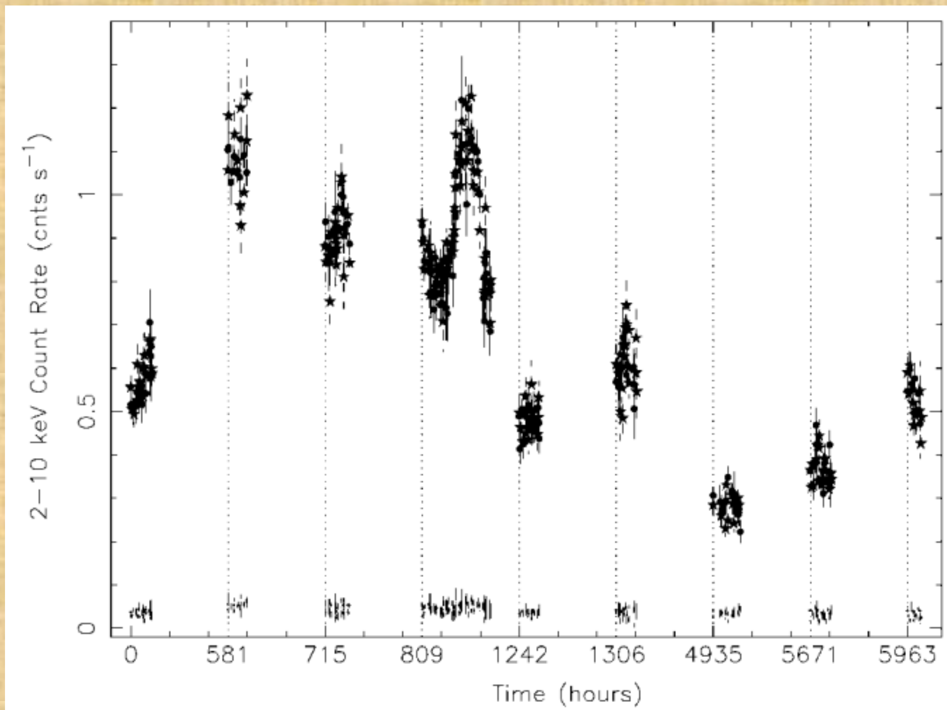
Expanding Supernova remnants?

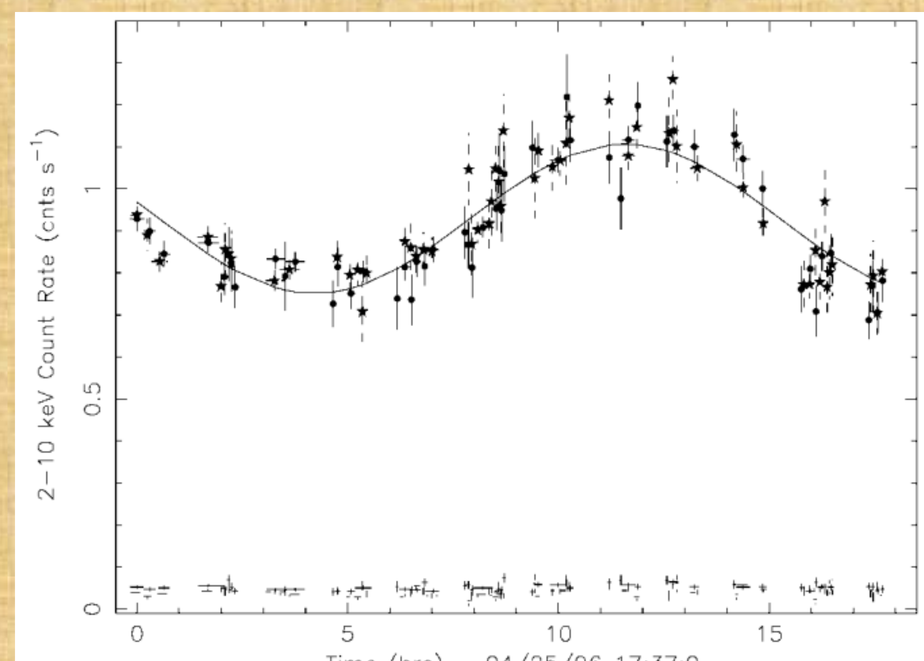
1999: using ASCA, X-1 in M82 was found to vary by up to a factor of four, confirming that this bright source was indeed a ***single object.***
*Over half of ULXs are known to be variable, ruling out the multiple source or SNR hypothesis.

We report on the detection of hard (2–10 keV) X-ray variability in the starburst galaxy M82 over the course of nine *ASCA* observations. Long-term variability occurred on a timescale of days, with a change in flux by a factor of up to ~4, corresponding to a point-source luminosity of $L_{2-10\ \mathrm{keV}} \sim 6 \times 10^{40}$ ergs s^{-1}. Short-term variability with an amplitude of ~1.4 on a timescale of hours was observed during the longest observation. This demonstrates that a large fraction of the hard X-ray emission of M82 (depending on the flux state) is from a compact region and is probably due to an accreting source. The 2–10 keV luminosity of the source is a lower limit to its Eddington luminosity, implying a black hole mass of at least ~460 $M_\odot$ or a mass intermediate to that of normal active galactic nuclei and stellar-mass black hole candidates.

ApJ, 517, L85 (1999)

ULXs—Early observations





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Single sources ?

Groups?

Expanding Supernova remnants?

*Whatever process ins forming these very luminous BHs is enhanced when many stars, particularly one of large mass and size, form simultaneously. And the production of the high-brightness X-ray sources goes away as fast as the star formation subsides.

1999: using ASCA, X-1 in M82 was found to vary by up to a factor of four, confirming that this bright source was indeed a ***single object.***
*Over half of ULXs are known to be variable, ruling out the multiple source or SNR hypothesis.

Recent studies show that they don't seem to be associated with large star clusters and in a few cases are actually HMXBs.

In a 2002 simulation of star clusters, cluster center massive stars merge to form a very massive star >100 $M_{\odot}$ and continue to grow to ~0.1% cluster mass then collapsed into a BH.

ULXs—Temperature problem

For BH accreting near Eddington limit, it would have temperature

$$T_{rad} \approx 0.23\,keV \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right)^{1/4} \left(\frac{M}{1000\,{\rm M}_\odot}\right)^{-1/4}$$

Most ULXs have 1-2keV temperature (4-9 times higher)

$$T_* = 1.5 \times 10^7\,{\rm K} \times \left(\frac{M}{{\rm M}_\odot}\right)^{-1/4} \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right)^{1/4} \left(\frac{R}{6\,r_g}\right)^{-3/4} \left[1 - \left(\frac{R}{r_{\rm isco}}\right)^{-1/2}\right]^{1/4}$$

Some explanations:

--super-Eddington luminosities--

1. IMBHs could be spinning. A factor of 4 could be gained if we use R~r_g instead of 6 r_g
2. Object could be slightly super-Eddingtim with $m \approx 3$. Given a thin disk then we can gain a factor of 6 in temperature due to seeing radiation produced deep in the disk.

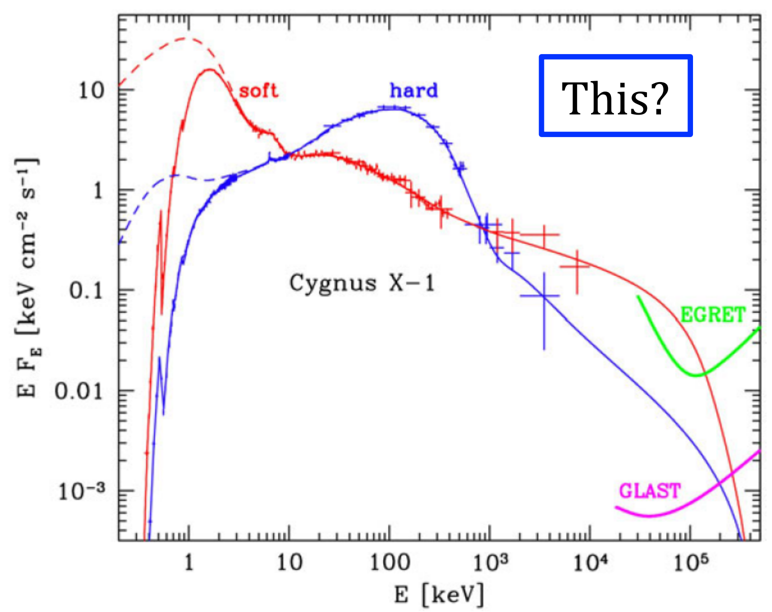
--non-super-Eddington luminosities--

3. The X-rays could be beamed either by reflection off the accretion disk or by a jet.
4. Magnetized accretion disks could produce luminosities greater than L_{Edd} - up to 10x for microquasars.

The isotropic luminosity might only be 1/10 of previous estimates! Previous mass estimates fails to give masses in the IMBH range!

ULXs—Temperature problem

* Increasingly, observers are finding that there often is, indeed, a "soft X-ray excess" or peak near 0.1 keV in many ULXs, particularly the brightest ones. This may solve the high-temperature problem for many ULXs and revive the IMBH proposal.



Independent estimates of the isotropic luminosity (e.g., from reflection by, or ionization of, a surrounding nebula) will be needed to counter the beaming argument. And independent estimates of the black hole masses (e.g., via the motion of a binary or additional stellar neighbors) may be needed to finally settle the controversy.

ULXs—in ellipticals

Although ULXs are mostly associated with rapid SF, they are also found in ellipticals.

High luminosity ULXs

Occur in globular clusters
Tend to be quite variable.

Possible IMBH candidate?

Example:
A black hole, RZ 2109 was found in a globular cluster in NGC 4472. It emits $4.5*10^{39}$ erg/s in0.2-12keV with a soft temperature T~0.2keV.
*would be 35 $M_\odot$ if radiating at Eddington limit.

A team led by Stephen Zepf of Michigan State University observed the oxygen lines produced by the black hole source in RZ 2109 and found them to be very broad, about 2000 $\mathrm{km\,s^{-1}}$ [278]. Such a high velocity in a globular cluster, with a velocity dispersion of perhaps only 10–20 $\mathrm{km\,s^{-1}}$, this high-velocity flow might be due to a super-Eddington wind generated by the black hole accreting at much greater than the Eddington limit. (See Sections 13.1.2 and 16.2.3.) The implications of this observation are significant. The time for a 35 $M_\odot$ object to sink to the center of a cluster is only a couple of million years (equation (10.11)). So, if there were an intermediate mass black hole at the center, it is possible that it would have ejected this stellar-mass black hole from the cluster and certainly have tidally disrupted the binary system that is feeding the latter. Zepf and his team concluded, therefore, that there is no IMBH in this globular cluster.

Low luminosity ULXs

Don't seem to be associated with any object.
Don't vary much.

More consistent with old, high-luminosity LMXBs.

Almost half of ULXs in ellipticals (particularly those thought to be in their halos) appear to be background sources. So, previous statements that most ULXs in ellipticals lay in their halos were incorrect; instead, most actually lie in the body of the galaxy itself.

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Globular clusters—the motivation

1. If ULXs in globular clusters are IMBHs, could we find dormant IMBHs in globular clusters close to us by other means? (Kinematics etc…)

2. Dwarf galaxies have SMBH $\sim 8 \times 10^{4}\ M_{\odot}$, might spheroidal globular cluster also harbor BHs? If they also follow the 0.1% mass relation, then they would be $10^{3-4}\ M_{\odot}$.

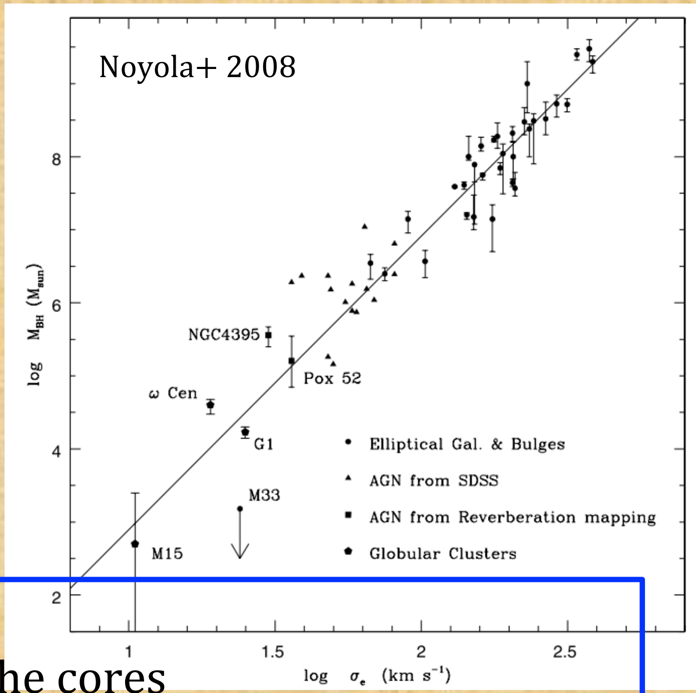
Globular clusters—the 2 massive candidates

2002: G1 cluster ($1.5 \times 10^{7}\ M_{\odot}$) in Andromeda galaxy was found using velocity profiles to host $2 \times 10^{4}\ M_{\odot}$ BH.

2007 A radio source was found at the center of G1 with L_{radio} / L_{X} similar to other accreting BHs.

2008: A $4 \times 10^{4}\ M_{\odot}$ BH was found at the center of Milky Ways' largest globular cluster ω Cent.

Are they the missing link "IMBH"s that we have been looking for?



Problems:
These two star systems have more in common with the cores of dwarf elliptical galaxies than with standard globular clusters. For this reason, it has been suggested that the two are, in fact, partially stripped dwarf ellipticals that have been captured by their respective spiral hosts.

Globular clusters— another candidate

2002:
Possible detection of ~1700 $M_\odot$ black hole in the globular cluster M15 being consistent with M-σ relation.

This could also be explained by "mass segregation" – heavy (>1 $M_\odot$) WD & NS sinking to the center of the cluster, mimicking the effects of an IMBH.

These investigators also pointed out that,
if there were an IMBH at the center of a globular cluster, it would not necessarily have a collapsed core like these(?) candidates. Indeed, their simulations showed that clusters with a black hole in the center could have a normal distribution of stars, with a fairly large cluster core radius. The black hole certainly would have an effect on the density of stars near it, but only at a radius well inside 1% of the globular cluster core radius and only affecting a few tens of stars or so

?

If correct, this would call into question all dynamical evidence for IMBHs presented so far. This does not mean that an IMBH is not at the center of many or most globular clusters, only that proving so will be much more challenging than originally anticipated.

Globular clusters— more problems

2008, three globular clusters surveyed (including M15) in radio did not detect a central black hole radio source in any – down to a Bondi accretion rate of 0.01%.

This is 100 times lower (in Bondi units) than G1.

Therefore, there still is no evidence of any kind that true globular clusters harbor IMBHs in their centers that are anywhere near a mass of 0.1–0.2% of the cluster mass.

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The galactic center—historical background

1975: 19 IR sources found near galactic center.

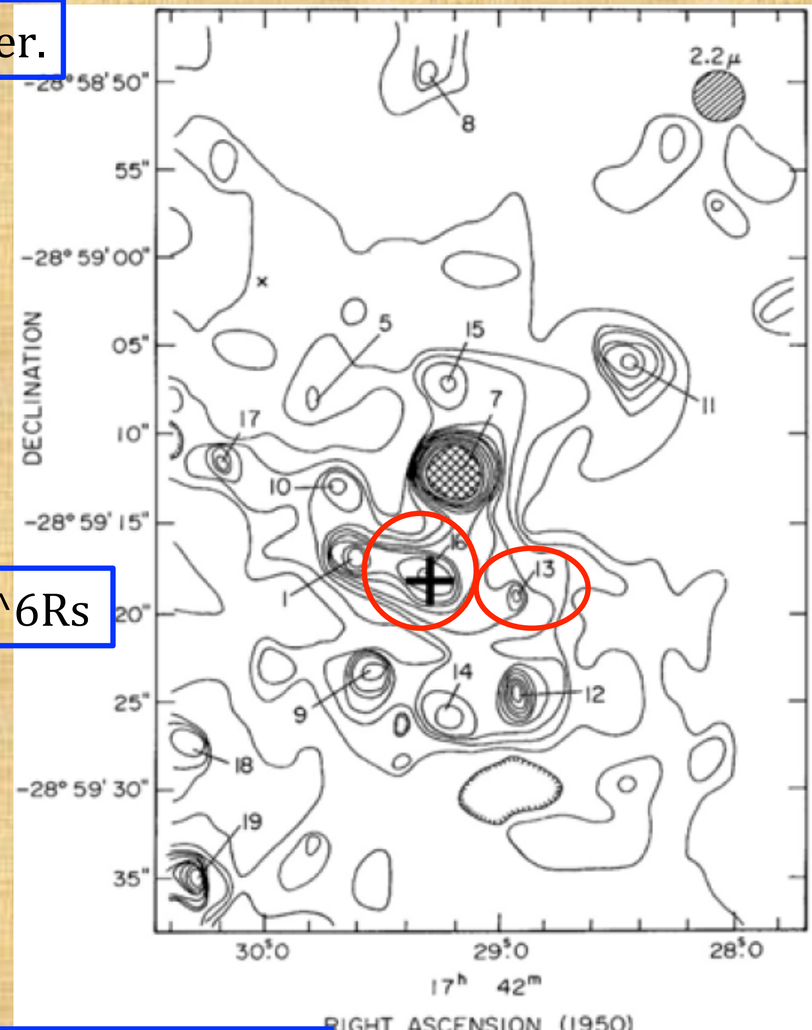
Later 0.5'' resolution imaging showed that
1. IRS 13 (~0.2pc from SMBH)
2. IRS 16 (~0.1pc from SMBH)
3. Group of bright stars centered on the SMBH (~0.2pc)

*all appear to be very young, ~Myr

Stars should not be able to form inside 10pc of the strong, tidal gravity of the SMBH.

It would take Gyrs for stars formed >10pc away to migrate inward.

How did those young stars wind up so close to the SMBH?



0.1pc~10^6Rs

The galactic center—the theoretical aspect

In 2003, theorists conclude that these young stars indeed could have migrated into the center in a few million years, but only if they remained bound in a compact, very heavy cluster of stars that rapidly sank toward the center of the Galaxy.

If it were only a star cluster, then it would have been torn apart well beyond there they lie now.

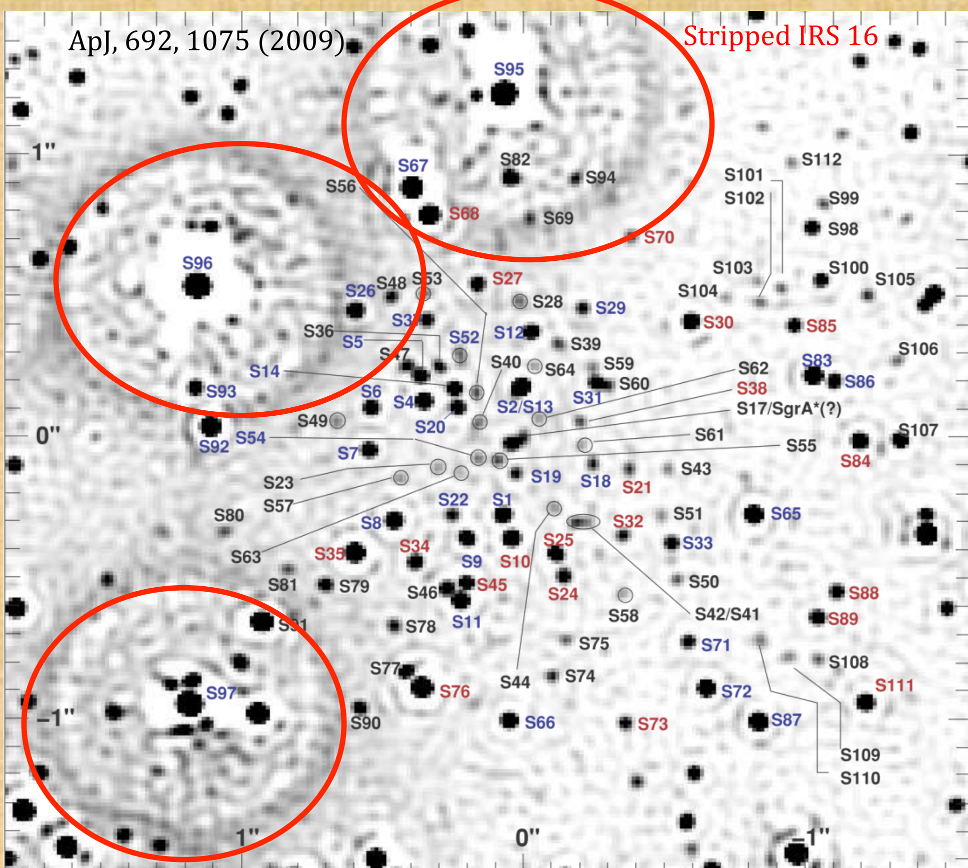
Another BH of $\sim 10^{3} \sim 10^{4}\ M_{\odot}$ would be needed to hold them together.

Observed features (prev. page)
1. IRS 13 (~0.2pc from SMBH)
2. IRS 16 (~0.1pc from SMBH)
3. Group of bright stars centered on the SMBH (~0.2pc)

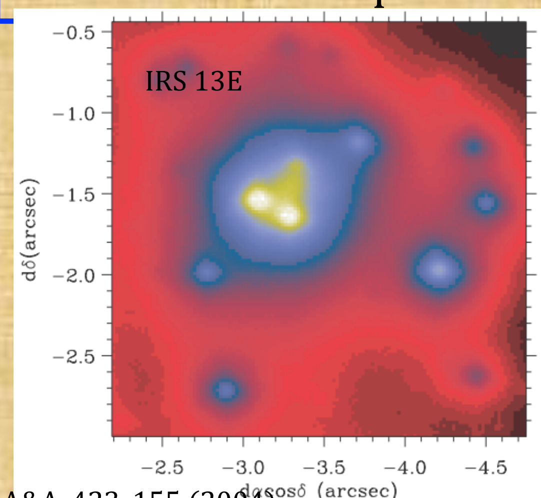
The scenario:
1. A massive $\sim 10^{6}\ M_{\odot}$ star cluster formed it's own IMBH $\sim 10^{3}\ M_{\odot}$
2. The cluster sank toward the SMBH via dynamical friction
3. Somewhere inside 0.1~0.2pc the SMBH's tidal forces finally overcome the binding of the IMBH and stripped the cluster.

The galactic center—detailed observations

In 2004, IRS 13E was resolved into 20 distinct stars with 0.04'' NIR imaging. Unlike IRS 16, IRS 13E is very compact and not being tidally disrupted into a ring of stars by the SMBH.
By following the stellar motions, the dark mass was found to be greater than $10^3\ M_\odot$.



Based on these preliminary results, Portegies Zwart and his group have predicted that there may be as many as 50 additional one-thousand solar mass IMBHs within 10 pc of our central SMBH.



A&A, 423, 155 (2004)

Fig. 1. IRS 13 field from the Gemini AO image in the *K*p band. IRS 13E is the central, compact group of stars and IRS 13W the brightest source ~1'' southwest of IRS 13E. The coordinates are in arcsec offset from SgrA*.

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Hard X-Ray Sources in the Galactic Bulge

IMBH
- Very bright, soft sources (ULXs)
- Emitting no detectable radiation (globular cluster cores, IRS 13E)
- How about sweeping up small amounts of gas and shining faintly?

In Chap. 11, we will learn that the Bondi accretion rate for this process of sweeping up gas is:

$$\dot{M} \approx 10^{17}\,\mathrm{g\,s^{-1}} \left(\frac{M}{10^3\,\mathrm{M_\odot}}\right)^2 \left(\frac{\sigma_\mathrm{V}}{70\,\mathrm{km\,s^{-1}}}\right)^{-3} \left(\frac{n}{100\,\mathrm{cm^{-3}}}\right) \qquad (4.1)$$

Taking typical $10^3\ M_\odot$ IMBH mass, 70km/s as Galactic bulge σ_v, and $100\,cm^{-3}$ as typical number density, and assuming ADAF model for accretion at low rates (sec 12.2.2), the luminosity would be

$$\begin{aligned} L_X &= \epsilon_\mathrm{acc}\,\dot{M}\,c^2 \\ &\approx 6\times10^{34}\,\mathrm{erg\,s^{-1}} \left(\frac{M}{10^3\,\mathrm{M_\odot}}\right)^3 \left(\frac{\sigma_\mathrm{V}}{70\,\mathrm{km\,s^{-1}}}\right)^{-6} \left(\frac{n}{100\,\mathrm{cm^{-3}}}\right)^2 \end{aligned}$$

--this estimate is of course strongly dependent on the parameters- -

*If σ_v were increased to 150km/s then the luminosity would drop by 2 orders of magnitude.

*If in the case we take a $10^4\ M_\odot$ BH, then the luminosity would increase by 3 orders of magnitude.

Hard X-Ray Sources in the Galactic Bulge

What would these weak X-ray sources look like?

By analogy of weak X-ray binaries and LLAGNs, they should be
*hard X-ray sources with
*a large fraction of their emission in the 10-100 keV region

According to ADAF model, they could remain hard X-ray sources until they reach $m \sim 0.03-0.1$

They would appear as hard X-ray sources with $Lx \sim 10^{34-37}$ erg/s

INTEGRAL & Chandra show:
~60 hard sources down to 10^{35} erg/s within 1kpc of the Galactic center,
2000 sources down to 10^{31} erg/s within ~20kpc,

If Portegies Zwart's team's estimates are correct, then several hundred of these hard, weak X-ray sources (10–20% of them) could be IMBHs. This fraction would not contradict current ideas that most of these faint sources are cataclysmic variable binaries with a magnetized white dwarf and a MS star.

Radio searches for Low-Luminosity miniquasars?

Tom Maccarone and his team suggest that an even better method of finding low-luminosity miniquasars would be to search for them in the radio region, at 5GHz, the predicted radio flux would be

$$F_{5\,\mathrm{GHz}} = 9.4\,\mathrm{mJy}\left(\frac{L_X}{6.5\times10^{34}\,\mathrm{erg\,s^{-1}}}\right)^{0.6}\left(\frac{M_\bullet}{10^3\,\mathrm{M_\odot}}\right)^{0.78}\left(\frac{d}{8\,\mathrm{kpc}}\right)^{-2} \quad (4.3)$$

Summary

I don't think I can make it any more concise here…

Several candidate sources and objects have been suggested as harboring intermediate mass black holes:

- ultra-luminous and hyper-luminous *soft* X-ray sources (with more than a quarter million solar luminosities in X-rays alone), both in regions of very rapid star formation and in old globular clusters;
- possible dark concentrations of matter of perhaps $10^{3-4}\,M_\odot$ at the centers of globular clusters;
- a dark concentration of dark matter at the center of the compact, young star cluster IRS 13E that lies within 0.2 pc of our own Galaxy's *supermassive* hole;
- faint, *hard* X-ray sources within 20 pc of our Galactic center, and presumably near the centers of other galaxies as well.

All of these have very plausible alternative explanations. The strongest identification appears to the IRS 13E one, although additional observational work on the source has produced only "tantalizing but presently unconvincing" evidence of the presence of an IMBH there [132]. Data will be needed to confirm the detection. The latter observation has direct dynamical evidence, in addition to the indirect arguments that such a large secondary black hole is needed to drag in the very young stars observed near the Galactic center.

The next strongest identifications are the HLX sources (the few with luminosities exceeding 10^{41} erg s^{-1}) found in regions of rapid star formation. Their properties strain the beaming and super-Eddington emission alternative explanations and, taken again with the theoretical expectation of IMBHs in young, compact star clusters, the identification of the very brightest ULXs with intermediate mass black holes seems very plausible.

If the IRS 13E result can be confirmed, it will be of tremendous significance to astrophysics. It will mean that

- IMBHs *do* exist;
- they indeed can be formed at the center of massive, compact star clusters, as predicted theoretically;
- such black holes can, and do, get well within 1 pc of a supermassive black hole;
- and these IMBHs and their stars probably can merge with the SMBH (toward which they are inspiraling) at a rate that could account for much of the central SMBH's mass itself.

Furthermore, the existence of an IMBH in a very young star cluster will mean that, while many of the ULX sources found in star-forming galaxies may be regular high-mass X-ray black hole binaries, some indeed probably *are* IMBHs in newly-formed compact star clusters – most likely the brightest and softest HLX ones, with luminosities approaching 25 million solar luminosities in soft X-rays alone.

The field of IMBH study has the potential to link stellar and supermassive black holes, not only in mass and luminosity but also in their processes of formation and evolution. It is a brand new field, only a few years old, and should see significant growth in the next decade.