reservoir. Practical cell-sorting requires significantly higher purities. The authors' model suggests this could be improved by slowing the cell-division process, increasing the directional bias of each step, or by increasing the migration rate. Whether these can be accomplished is unclear, but at least they provide a solid framework to build on.

The exact mechanism for this directed migration will also need to be more clearly identified — in particular given the conflicting directions of migration observed by Jiang, Kumar and Mahmud. Here again, Mahmud *et al.* provide a good starting point from which to proceed, because by tailoring the shapes of their patterns, they can alter the shapes of the cells (and their cytoskeleton), providing the means to test hypotheses about the mode of action.

At the very least, the work provides an innovative approach to modelling the behaviour of complex systems, a method that has been perfected in the design of electrical circuits. This involves a hierarchical approach that allows a model to be constructed at many different scales of complexity, from the level of individual components described with basic device physics, to the level of circuits at which components interact, to larger blocks such as logic gates and even entire computer chips. Rather than trying to model the cell motion at a molecular level, this meant the authors could use an integrated picture of the cell as a diffusing object, allowing them to think about directing cell motion from the context of directing the motion of diffusing objects. This intermediate-scale model then allows researchers to either focus down on the mechanisms that govern the diffusion of individual objects — in this case, how migration occurs at the molecular level — or build up to design functional devices, such as how to fabricate large-scale systems to sort different cells from one reservoir to another. ❐

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References

1. Xia, Y. & Whitesides, G. M. *Angew. Chem. Int. Ed.* **37,** 550–575 (1998).
2. Mahmud, G. *et al. Nature Phys.* **5,** 606–612 (2009).
3. Li, S., Guan, J. L. & Chien, S. *Annu. Rev. Biomed. Eng.* **7,** 105–150 (2005).
4. Jiang, X. Y., Bruzewicz, D. A., Wong, A. P., Piel, M. & Whitesides, G. M. *Proc. Natl Acad. Sci. USA* **102,** 975–978 (2005).
5. Kumar, G., Ho, C. C. & Co, C. C. *Adv. Mater.* **19,** 1084–1090 (2007).

ASTROPHYSICS

A happy medium

The case for the existence of intermediate-mass black holes, hundreds to thousands of times more massive than our Sun, has received a major boost — with implications for gravitational waves and clustered star formation.

M. Coleman Miller

Astrophysical black holes are completely characterized by their mass and angular momentum, making them the simplest macroscopic objects in the Universe. From the mathematical standpoint their mass is unimportant, meaning that all black holes with a given scaled spin are fundamentally the same. However, the formation and evolution of the holes, as well as the implications for their environments and for gravitational radiation, depend rather strongly on the mass. As a result, astronomers have expended considerable effort in establishing the reality of black holes of different masses.

Their quest has been eminently successful for stellar-mass black holes (masses a few to a few tens of times that of our Sun, which evolve from single stars[1]) and for supermassive black holes (millions to billions of times the mass of our Sun, which inhabit the centres of most galaxies[2]). Astronomers have had less luck in demonstrating the existence of intermediate-mass black holes (hundreds to thousands of solar masses). This is unfortunate, because the formation and evolution of such black holes would have wide-ranging implications for the first stars in the Universe[3] and violent collapses in dense clusters of stars[4]. If such holes fall into supermassive black holes, future observations of the gravitational radiation from their inspiral could ultimately yield the most precise tests of the general theory of relativity in strong gravity[5].

The reason for our current uncertainty is that although we have direct dynamical measurements of masses for stellar-mass and supermassive black holes, these do not yet exist for intermediate-mass black holes. More specifically, there are more than 20 examples of stellar-mass black holes around which we can observe the orbit of an individual star, and thus constrain the hole's mass using Kepler's laws. Supermassive black holes control regions of space that are large enough such that the collective motion of the millions of stars around them can also be interpreted using Kepler's laws, thus leading directly to mass. In contrast, the best candidates for intermediate-mass black holes are too far away for easy observation of individual companions, and the holes themselves are too light to control a region that is big enough for it to be straightforward to resolve at such distances. These holes are thus caught in a realm that does not yet allow direct measurements of masses.

The community has therefore turned to more indirect approaches. As an example, the best candidates at present for intermediate-mass black holes are the so-called ultraluminous X-ray sources. These objects are accreting black holes bright enough at their distances from us that, if they emit equally in all directions, the force of their radiation would exceed the force of gravity at any distance if the hole were only of stellar mass, and would thus prevent the accretion that powers the emission. The standard interpretation is that this implies that the holes must have higher mass — that is, that they are intermediate-mass black holes. But doubt exists because there are models that have challenged these assumptions. For example, if the radiation can slip between clumps in the matter, or if it is beamed towards us, then these considerations could be evaded to a degree[6–8].

These alternative models have limits, however. The best estimates at present suggest that beaming and clumping can only buy you a factor of ~10 solar masses. If we generously allow stellar-mass black holes to extend up to a hundred times the mass of our Sun, this means that we would need a source with a standard limit at least a thousand times the mass of our Sun to be confident that it really is not an ordinary black hole, and thus requires a qualitatively


HEIDI SAGERUD

Figure 1 | An artist's impression of the candidate intermediate-mass black hole HLX-1 (bright spot just to the left of the bulge) and its spiral galaxy host. The bright feature to the right of the bulge is a foreground star.

new formation mechanism. Hundreds of ultraluminous X-ray sources are known, but until now none of them were beyond this threshold.

As reported by Sean Farrell and co-workers in *Nature*[9], observations using the XMM-Newton X-ray telescope have revealed such a source for the first time. Located on the outskirts of the galaxy ESO 243-49 (Fig. 1), and hence not a supermassive black hole itself, the mellifluously named ultraluminous X-ray source 2XMM J011028.1-460421 (also known as HLX-1) is bright enough that the standard lower limit to its mass would be 5,400 times the mass of the Sun. This mass is well beyond our threshold, and thus represents the best single case for the existence of intermediate-mass black holes.

But are there ways around the observation that do not require an intermediate-mass black hole? Several possibilities are discussed by Farrell *et al.* For example, if this source is not associated with ESO 243-49, it could either be a background supermassive black hole (which could easily reach the observed brightness) or a much closer object, such as a stellar-mass black hole or an accreting white dwarf. These possibilities are ruled out by a combination of probability arguments (based on the angular nearness to the galaxy) and the spectral properties of the source. A different option would be that the brightness indicates the superposition of many unresolved sources, rather than a single bright object. However, significant variation is observed in the spectrum of the source, so unless we postulate that many sources are conspiring to vary in concert, a single source must dominate the emission. Another apparent explanation would be that the alternative modellers have been too conservative, and that, for instance, very tight beaming could account for the high brightness we see. In this case, however, the radiation force in our direction would be sufficient to drive matter to highly relativistic speeds, leading to an X-ray spectrum in conflict with that observed[10].

Arguments will no doubt continue until masses are measured directly. However, in the meantime, Farrell *et al.* have presented the strongest evidence so far that intermediate-mass black holes exist. This is encouraging news for modellers of gravitational radiation sources, early stars and dense stellar clusters, and will motivate renewed study of this happy medium in black-hole masses. ❒

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References

1. Remillard, R. A. & McClintock, J. E. *Ann. Rev. Astron. Astrophys.* **44,** 49–92 (2006).
2. Ferrarese, L. & Ford, H. *Spac. Sci. Rev.* **116,** 523–624 (2005).
3. Madau, P. & Rees, M. J. *Astrophys. J.* **551**, L27–L30 (2001).
4. Portegies Zwart, S. & McMillan, S. L. W. *Astrophys. J.* **576,** 899–907 (2002).
5. Miller, M. C. *Astrophys. J.* **618,** 426–431 (2005).
6. Reynolds, C. S. *et al. Mon. Not. R. Astron. Soc.* **286,** 349–357 (1997).
7. King, A. R. *et al. Astrophys. J.* **552**, L109-L112 (2001).
8. Ruszkowski, M. & Begelman, M. C. *Astrophys. J.* **586,** 384–388 (2003).
9. Farrell, S. A. *et al. Nature* **460,** 73–75 (2009).
10. Freeland, M. *et al. Mon. Not. R. Astron. Soc.* **372,** 630–638 (2006).

ATOM CHIPS

Read the labels

Compact interferometers that exploit the wave character of atoms have the potential to outpace their optical counterparts in a number of sensing applications. A technique that harnesses the internal structure of atoms should bring such applications a step closer.

Chris Westbrook

Atom interferometry holds great promise for the detection of inertial effects, acceleration, rotation and gravitation. Compared with optical interferometry, atoms have, for example, an intrinsic sensitivity to rotation, which is increased by the ratio of their rest energy to the energy of the photon — some ten orders of magnitude[1]. The past decade has seen the development of 'atom chips', devices in which atoms are trapped tens of micrometres above a solid substrate in the magnetic field created by wires on the surface[2]. A driving motivation for atom chips has been that compact, light and robust devices containing atom interferometers on a chip might, one day, fly to space or travel under the sea, bringing the power of atom interferometry to new environments. So one might dream of mapping out the gravitational