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Accretion onto Black Holes and Neutron Stars

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Abstract A black hole is a region of space in which the matter is so compact that nothing can escape from it, not even light; the "surface" of a black hole, inside of which nothing can escape, is called an event horizon. The matter that forms a black hole is crushed out of existence. Just as the Cheshire Cat disappeared and left only its smile behind, a black hole represents matter that leaves only its gravity behind. Black holes are usually formed when an extremely massive star dies in a supernova. However, some people think small black holes were formed during the Big Bang, and that the resulting "mini black holes" may be in great abundance in our galaxy. In reality, it is known that this limit can be violated, due to non-spherical geometry or various kinds of instabilities. Nevertheless, the Eddington limit remains an important reference point, and many of the details of how accretion proceeds above this limit remain unclear [Gregory B. Poole Chris Blake, David Parkinson, 2012]. Understanding how this so-called super-Eddington accretion occurs is of clear cosmological importance, since it potentially governs the growth of the first supermassive black holes (SMBHs) and the impact this growth would have had on their host galaxies and the epoch of reionization, as well as improving our understanding of accretion physics more generally.

Keywords Black Holes, Accretion, Gravity, Neutron Stars, Supermassive Hole

1. Introduction

Accreting black holes and neutron stars at luminosities above 0.01 of the critical Eddington luminosity have a lot of similarities, but also drastic differences in their radiation and power density spectra. The efficiency of energy release due to accretion onto a rotating neutron star usually is higher than in the case of a black hole. The theory of the spreading layer on the surface of an accreting neutron star is discussed. It predicts the appearance of two bright belts equidistant from the equator. This layer is unstable and its radiation flux must vary with high frequencies. Gravitational potential energy release for an object with mass M and with radius R by accretion of a test particle with mass M. During the last ten years, the launch of X-ray telescopes with unprecedented capabilities, such as RXTE, Beppo SAX, the Chandra X-ray Observatory, and XMM-Newton opened new windows onto the properties of accreting compact objects. Examples include the rapid variability phenomena that occur at the dynamical timescales just outside the neutron-star surfaces and the black-hole horizons as well as atomic lines that have been red- and blue-shifted by general relativistic effects in the vicinities of compact objects [M. Coleman Miller and Jon M. Miller, 2013]. Accreting neutrons stars and black holes have been monitored in broad spectral bands, from the radio to γ -rays, leading to the discovery of highly relativistic jets [[M. Coleman Miller and Jon M. Miller, 2013].], to the indirect imaging of the accretion flows, and to the possible identification of neutron stars with masses close to the maximum value allowed by general relativity [B. F. Schutz Max Planck, 2017].

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Where do Black Holes lead?

If that sounds like a disappointing — and painful — answer, then it is to be expected. Ever since Albert Einstein's general theory of relativity was considered to have predicted black holes by linking space-time with the action of gravity, it has been known that black holes result from the death of a massive star leaving behind a small, dense remnant core. Assuming this core has more than roughly three-times the mass of the sun, gravity would overwhelm to such a degree that it would fall in on itself into a single point, or singularity, understood to be the black hole's infinitely dense core. The resulting uninhabitable black hole would have such a powerful gravitational pull that not even light could avoid it. So, should you then find yourself at the event horizon — the point at which light and matter can only pass inward, as proposed by the German astronomer Karl Schwarzschild — there is no escape. According to Massey, tidal forces would reduce your body into strands of atoms (or 'spaghettification', as it is also known) and the object would eventually end up crushed at the singularity. The idea that you could pop out somewhere — perhaps at the other side — seems utterly fantastical. [Space is part of Future US Inc, an international media group and leading digital publisher, 2019]. Step forward Hawking once more. In 2014, he published a study in which he eschewed the existence of an event horizon — meaning there is nothing there to burn — saying gravitational collapse would produce an 'apparent horizon' instead. This horizon would suspend light rays trying to move away from the core of the black hole, and would persist for a "period of time." In his rethinking, apparent horizons temporarily retain matter and energy before dissolving and releasing them later down the line. This explanation best fits with quantum theory — which says information can't be destroyed — and, if it was ever proven, it suggests that anything could escape from a black hole. [Stephen Hawking's Best Books: Black Holes, Multiverses and Singularities, 2010]

Hawking went as far as saying black holes may not even exist. "Black holes should be redefined as metastable bound states of the gravitational field," he wrote. There would be no singularity, and while the apparent field would move inwards due to gravity, it would never reach the center and be consolidated within a dense mass.

What is the nature of Neutron Stars?

Neutron stars -- the compressed remains of massive stars gone supernova -- are the densest "normal" objects in the known universe. (Black holes are technically denser, but far from normal.) Just a single sugar-cube worth of neutron-star material would weigh 100 million tons here on Earth, or about the same as the entire human population. Though astronomers and physicists have studied and marveled at these objects for decades, many mysteries remain about the nature of their interiors: Do crushed neutrons become "superfluid" and flow freely? Do they breakdown into a soup of subatomic quarks or other exotic particles? What is the tipping point when gravity wins out over matter and forms a black hole? [Materials provided by **Green Bank Observatory**., 2019.]

The researchers, members of the NANOGrav Physics Frontiers Center, discovered that a rapidly rotating millisecond pulsar, called J0740+6620, is the most massive neutron star ever measured, packing 2.17 times the mass of our Sun into a sphere only 30 kilometers across. This measurement approaches the limits of how massive and compact a single object can become without crushing itself down into a black hole. Recent work involving gravitational waves observed from colliding neutron stars by LIGO suggests that 2.17 solar masses might be very near that limit. [Materials provided by **Green Bank Observatory**., 2019.]

"Neutron stars are as mysterious as they are fascinating," said Thankful Cromartie, a graduate student at the University of Virginia and Grote Reber pre-doctoral fellow at the National Radio Astronomy Observatory in Charlottesville, Virginia. "These city-sized objects are essentially ginormous atomic nuclei. They are so massive that their interiors take on weird properties. Finding the maximum mass that physics and nature will allow can teach us a great deal about this otherwise inaccessible realm in astrophysics."

- Always in SN explosions
- If the collapsing core is more massive than the Chandrasekhar limit (~1.4 M¤), it cannot become a white dwarf
- Atomic nuclei are dissociated by γ-rays, protons and electrons combine to become neutrons:
- The collapsing core is then a contracting ball of neutrons, becoming a neutron star
- A neutron star is supported by a degeneracy pressure of neutrons, instead of electrons like in a white dwarf
- Its density is like that of an atomic nucleus, ρ~ 1015g cm–3, and the radius is ~ 10 km. [Ay 1 – Lecture 1, 2018]. Regarding the structure of Neutron Stars we should say Not quite one gigantic atomic nucleus, but sort of a macroscopic quantum object A neutron star consists of a neutron superfluid, superconducting core surrounded by a superfluid mantle and a thin, brittle crust.

2. Main Debate

Massive galaxy clusters are now found as early as 3 billion years after the Big Bang, containing stars that formed at even earlier epochs. The high-redshift progenitors of these galaxy clusters, termed ‘protoclusters’, are identified in cosmological simulations with the highest dark matter overdensities. While their observational signatures are less well defined compared to virialized clusters with a substantial hot intracluster medium (ICM), protocolusters are expected to contain extremely massive galaxies that can be observed as luminous starbursts. [T. B. Miller, 2018]

Recent claimed detections of protoclusters hosting such Starbursts do not support the kind of rapid cluster core formation expected in simulations 12 because these structures contain only a handful of star bursting galaxies spread throughout a broad structure, with poor evidence for eventual collapse into a protocluster. Here we report that the source SPT2349-56 consists of at least 14 gas-rich galaxies all lying at z = 4.31 based on sensitive observations of carbon monoxide and ionized carbon. We demonstrate that each of these galaxies is forming stars between 50 and 1000 times faster than our own Milky Way, and all are located within a projected region only 130 kiloparsecs in diameter. This galaxy surface density is more than 10 times the average blank field value (integrated over all redshifts) and >1000 times the average field volume density. The velocity dispersion (410 km s1) of these galaxies and enormous gas and star formation densities suggest that this sys-tem represents a galaxy cluster core at an advanced stage of formation when the Universe was only 1.4 billion years old. A comparison with other known protoclusters at high redshifts shows that SPT2349-56 is a uniquely massive and dense system that could be building one of the most massive structures in the Universe today. [T. B. Miller, 2018]. The general theory of relativity predicts that a star passing close to a supermassive black hole should exhibit a relativistic redshift. In this study, we used observations of the Galactic Center star S0-2 to test this prediction. We combined existing spectroscopic and astrometric measurements from 1995–2017, which cover S0-2's 16-year orbit, with measurements from March to September 2018, which cover three events during S0-2's closest approach to the black hole. We detected a combination of special relativistic and gravitational redshift, quantified using the redshift parameter ϒ. Our result, ϒ = 0.88 ± 0.17, is consistent with general relativity (ϒ = 1) and excludes a Newtonian model (ϒ = 0) with a statistical significance of 5σ.

Overall, there are believed to be only a few hundred accreting high-mass and low-mass X-ray binaries in the whole galaxy. Consequently, these binaries are extremely rare among stellar systems. This is in accord with the large number of improbable evolutionary steps a primordial binary needs to follow in order to become an X-ray source with an accreting compact object. Indeed, the progenitors of the compact objects are believed to be too large to fit in the tight orbits of most X-ray binaries. Moreover, the supernova explosions that precede the formation of the compact objects may disrupt most systems at the phase prior to the formation of the X-ray binary. The resolutions to these and other puzzles on the formation and evolution of X-ray binaries involve exotic and poorly understood binary-evolution processes such as common-envelope evolution of binary stars [A. Bauswein, 2012], asymmetric supernova explosions that impart recoil velocities to the newborn compact objects, and two- and three-star interactions in the dense stellar fields of globular clusters.

3. Accretion onto Compact Objects

An X-ray binary is formed when either the companion star transfers matter onto the compact object through the inner Lagrangian point or the compact object captures mass from the wind of the companion star. In both cases, the fate of the transferred mass depends on the amount of angular momentum it possesses, on the physical processes by which it looses angular momentum, and, most importantly, on the radiation processes by which it cools [S. Fujibayashi, 2016].

Beginning in the early 1970's and for the next two decades, most of the model-ing effort of accretion flows onto neutron stars and black holes was based on two restrictive assumptions. First, accretion flows were assumed to be loosing angular momentum at high rates because of an unspecified process, with the effective kinematic viscosity typically taken to be proportional to the pressure [J. L. Friedman, 2018].

Second, radiation processes were assumed to be very efficient, so that the resulting accretion flows were relatively cool, in the form of geometrically thin accretion disks. The first of these assumptions stemmed from calculations that showed the inefficiency of microscopic viscosity to account for the high inferred rates of mass accretion in the observed sources [C. Alcock, E. Farhi, and A. Olinto, 2017].

During the last decade, theoretical models of accretion flows onto compact objects became increasingly more sophisticated and diverse because of two major developments. First was the identification of a magneto hydrodynamic instability in differentially rotating flows [C. Alcock, E. Farhi, and A. Olinto,, 2017], which allows seed magnetic fields of infinitesimal strength in the flow to get enhanced and tangled. In planetary science, accretion is the process in which solids agglomerate to form larger and larger objects and eventually planets are produced. The initial conditions are a disc of gas and microscopic solid particles, with a total mass of about 1% of the gas mass. These discs are routinely detected around young stars and are now imaged with the new generation of instruments. Accretion has to be effective and fast. Effective, because the original total mass in solids in the solar protoplanetary disk was probably of the order of ~ 300 Earth masses, and the mass incorporated into the planets is ~100 Earth masses. Fast, because the cores of the giant planets had to grow to tens of Earth masses in order to capture massive doses of hydrogen and helium from the disc before the dispersal of the latter, i.e. in a few millions of years. [ACCRETION PROCESSES ALESSANDRO MORBIDELLI CNRS, OBSERVATOIRE DE LA COTE D'AZUR, NICE, FRANCE, 2019]

4. Conclusions

Extrasolar planet searches have shown that planet formation is a ubiquitous process around stars. Despite solid accretion is so easy for Nature, it is still hard to understand for human scientists. This is because of the wide range of spatial and temporal scales involved, which makes difficult to enact the accretion process in laboratory experiments or in virtual computer simulations. After decades of research, a new paradigm is emerging in which grain/pebble-size particles play the key role. In this paradigm, planetesimals would have been generated from self-gravitating clusters of these particles, which had clumped together due to their interaction with the (possibly turbulent) gas of the proto-planetary disk. Then, once formed, the largest planetesimals would have continued to accrete grains and pebbles individually but in large number, growing spectacularly in mass until becoming (proto) planets. Thus, we construct several rigidly rotating neutron stars in equilibrium as models of the remnant neutron stars at the onset of collapse. In The last four decades have been the period of discovery, in which the astrophysical properties of accreting compact objects were investigated. For his contribution to this effort, Riccardo Giaconni was awarded the 2002 Nobel price in physics. In the near future, the observations of neutron stars and black holes with detectors with large surface areas, high spectral resolution, and fast timing capabilities will allow for precise measurements of the physical conditions in the accretion flows, as they vary at the dynamical timescales near the compact objects. Moreover, the increase in the computational power and storage capabilities of supercomputers will allow for the development of new tools for modeling radiation-magneto-hydrodynamic phenomena in curved space times. And, as it has always been the case in compact-object astrophysics, this interplay between theory and observations will offer us a more complete picture of our universe.

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