OAM-astronomi – ett nytt sätt att studera universum och dess svarta hål

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Vad är OAM?

Som är välkänt kan elektromagnetisk strålning (fotoner), vare sig det är i våglängdsområdet för radio, ljus, Röntgen eller gamma, överföra information trådlöst över långa avstånd i form av elektromagnetisk fältenergi (en frihetsgrad) eller rörelsemängd (tre translationsfrihetsgrader), metoder som använts i både vetenskap och tekniktillämpningar i mer än ett århundrade. Mindre känt är att elektromagnetisk strålning också bär på rörelsemängdsmoment (sex rotationsfrihetsgrader) som även den kan överföra information trådlöst över långa avstånd. Samtliga dessa informationsbärande kvantiteter transporteras av fältet i form av volymetriska tätheter och kan därför alla sändas ut och tas emot av lämpligt konsturerade antenner av ändlig volym.

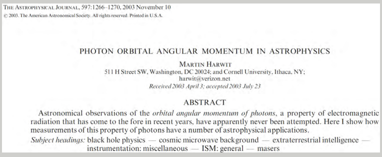
Elektromagnetiskt rörelsemängdsmoment består av två delar:

Spinnimpulsmoment (spin angular momentum, SAM). Denna kvantitet beskriver hur fälten (fotonerna) roterar i tiden, med- eller moturs, runt den egna utbredningsaxeln. SAM kallas också för cirkulär vänster- och högerpolarisation och har länge använts i radioastronomi och radiokommunikation.

Banimpulsmoment (orbital angular momentum, OAM). Denna kvantitet beskriver hur fälten (fotonerna) roterar i rummet kring en yttre punkt eller axel. Detta kallas skruvning. Medan OAM nu börjar utnyttjas i radiokommunikationer har den inte använts i radiobaserad astronomi eller rymdfysik. Förrän nu.

Förslag att utnyttja OAM i astrofysik framfördes först av Martin Harwit* men verkar inte ha förverkligats [1]; se mittfiguren i marginalen.

Observering av radiostrålning med OAM utsänd från den omedelbara närheten av svarta hål. Förenklad skiss.



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PHOTON ORBITAL ANGULAR MOMENTUM IN ASTROPHYSICS

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ABSTRACT

Astronomical observations of the *orbital angular momentum of photons*, a property of electromagnetic radiation that has come to the fore in recent years, have apparently never been attempted. Here I show how measurements of this property of photons have a number of astrophysical applications.

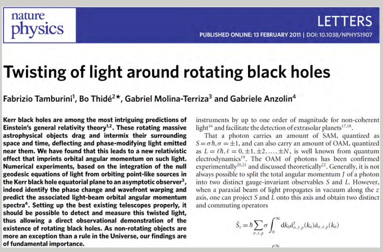
Subject headings: black hole physics — cosmic microwave background — extraterrestrial intelligence — instrumentation: miscellaneous — ISM: general — masers

Denna artikel i *The Astrophysical Journal* från 2003 nämner kortfattat möjligheten att OAM skulle kunna överföras från ett roterande svart hål till elektromagnetisk strålning som passerar i närheten, men inga fysikaliska mekanismer diskuterades och inga specifika resultat förutsades [1].

Förutsägelse om OAM-strålning från svarta hål

För nio år sen publicerade vi en teoretisk-numerisk artikel [2], baserad på Einsteins allmänna relativitetsteori, som förutsade att ljus- och radioemissioner från mycket nära ett roterande svart hål (Kerr-svarthål [3]) bär på OAM. Desstuom borde det från den spektrala strukturen hos detta OAM gå att bestämma storleken och andra egenskaper hos det svarta hålets spinn; se den undre figuren i marginalen.

Detta på grund av s.k. »frame dragging«† (ett fenomen där själva rumtiden släpas med av roterande svarta hål), gravitationslinseffekter, gravitationell Faradayrotation, gravitationell Berryfas och andra allmänrelativistiska effekter. Våra teoretiska undersökningar och numeriska simuleringar hade visat att ljus- och radioemissioner som inte genereras i den omedelbara närheten av det svarta hålet påverkas bara mycket svagt. D.v.s. om OAM-spektra skulle kunna detekteras överhuvudtaget, måste strålningen skapas i ergosfären‡, alldeles utanför det svarta hålets yttre händelsehorisont.



nature physics — LETTERS
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Twisting of light around rotating black holes

Fabrizio Tamburini[1], Bo Thidé[2]*, Gabriel Molina-Terriza[3] and Gabriele Anzolin[4]

Kerr black holes are among the most intriguing predictions of Einstein's general relativity theory[1,2]. These rotating massive astrophysical objects drag and intermix their surrounding space and time, deflecting and phase-modifying light emitted near them. We have found that this leads to a new relativistic effect that imprints orbital angular momentum on such light. Numerical experiments, based on the integration of the null geodesic equations of light from orbiting point-like sources in the Kerr black hole equatorial plane to an asymptotic observer[3], indeed identify the phase change and wavefront warping and predict the associated light-beam orbital angular momentum spectra[4]. Setting up the best existing telescopes properly, it should be possible to detect and measure this twisted light, thus allowing a direct observational demonstration of the existence of rotating black holes. As non-rotating objects are more an exception than a rule in the Universe, our findings are of fundamental importance.

instruments by up to one order of magnitude for non-coherent light[16] and facilitate the detection of extrasolar planets[17,18].

That a photon carries an amount of SAM, quantized as $S = \sigma\hbar, \sigma = \pm 1$, and can also carry an amount of OAM, quantized as $L = \ell\hbar, \ell = 0, \pm 1, \pm 2, \ldots, \pm N$, is well known from quantum electrodynamics[19]. The OAM of photons has been confirmed experimentally[20,21] and discussed theoretically[22]. Generally, it is not always possible to split the total angular momentum J of a photon into two distinct gauge-invariant observables S and L. However, when a paraxial beam of light propagates in vacuum along the z axis, one can project S and L onto this axis and obtain two distinct and commuting operators

$$\hat{S}_z = \hbar \sum_{\sigma,\ell,p} \sigma \int_0^\infty dk_0 \hat{a}^\dagger_{\sigma,\ell,p}(k_0) \hat{a}_{\sigma,\ell,p}(k_0)$$

Inledningen av vår artikel i *Nature Physics* från februari 2011 där vi förutsade OAM i ljus/radio som emitteras nära ett roterande svart hål [2].

*https://en.wikipedia.org/wiki/Martin_Harwit
†https://en.wikipedia.org/wiki/Frame-dragging
‡https://en.wikipedia.org/wiki/Ergosphere

Observationell bekräftelse av förutsägelserna

Den 10:e april 2019 presenterade *Event Horizon Telescope (EHT) collaboration*[§] radiobilder i 1,3 mm våglängd av den mörka skuggan runt det supermassiva svarta hålet M87* beläget på 55 mijoner ljusårs avstånd i galaxen Messier 87 inom Virgohopen och gjorde dessa radiobilder allmänt tillgängliga online två dagar senare. Denna första avbildning av ett svart hål var en banbrytande prestation som omedelbart blev viral.

Dessvärre tillhandahöll EHT-radiobilderna inte någon direkt infromation om OAM (skruvning). Men en serie lyckosamma betingelser, såsom det svarta hålets rörelse relativt jorden, radiovågutbredningens stabilitet, och en minutiöst noggrann dataanlays gjorde att vi inom en vecka kunde bekräfta att radiostrålningen utsänd från den omedelbara närjeten av M87* verkligen var skruvad. En analys av den OAM som på så sätt upptäcktes bekräftade att den hade alla de Kerr-svarthålssignaturer som vi hade förutsagt i vår artikel i *Nature Physics* 2011 [2]. Se översta figuren i marginalen.

Resultat och upptäckter

Inte bara bekräftade vi förutsägelsen att radiodata från EHT visar att OAM utstrålas kring M87*. Vi kunde också visa med 6σ konfidensnivå (99.99999998% säkerhet) att M87* verkligen roterar. Dessutom visade OAM-dataanalysen att spinnhastigheten är nära den maximala, svarande mot en periferihastighet på nära halva ljushastigheten. Vi kunde också mäta spinnets lutningsvikel och konstatera att rotationen sker medurs.

Genom att använda en välkänd formel från den allmänna relativitetsteorin för att beräkna den rotationsenergi som är härbärgerad i M87* fann vi att den är ofantlig (åtminstone 10^{63} erg $= 10^{56}$ Joule). Rotationsenergin hos M87* är alltså högre än den som totalt produceras i hela Vintergatan under hela dess tio miljarder år långa livslängd! Se näst översta figuren i marginalen.

En ytterligare bonus är att våra resultat från verkligheten visar att elektromagnetiskt OAM kan färdas ett avstånd på 55 miljoner ljusår och fortfarande vara mätbart. Detta bevisar att jämfört med konventionell radio har trådlös kommunikation baserad på OAM-radio inga ytterligare begränsingar på hur lång en OAM-radiokommunikationslänk kan vara, vilket motbevisar påståenden om motsatsen.

Utblick

I sin nyhetsartikel i *Nature Physics* 2011 om våra förutsägelser skrev professor Martin Bojowald[¶] vid Pennsylvania State University: »Det skruvade ljuset skulle kunna avslöja fysiken för svarta hål i mer detalj än vad som tidagre bedömdes vara möjligt…Dessa resultat öppnar vägen till nya observationella tester av allmän relativitet…skruvning av ljus öppnar redan nu vägen till spännande nya möjligheter i svarta-hålfysiken.« Se näst understa figuren i marginalen.

År 2011 skrev Edwin Cartlidge följande i en nyhetsartikel i *Nature* om våra nya idéer [6]: »Richard Matzner, astrofysiker vid University of Texas at Austin, håller med om att de föreslagna mätningarna skulle ge oss en mycket bättre uppfattning om vad som händer nära svarta hål. Han påpekar också att studium av det fasfördelningsmönster som Tamburini och hans kollegor upptäckt skulle kunna ge ytterligare experimentbevis för den allmänna relativitetsteorin.« See understa figuren i marginalen.

De observationella resultat vi nu publicerar [4] och som bekräftar att OAM-astronomi fungerar som förutspått [2] kommer sannolikt att bereda vägen för de typer av nya experiment som just nämnts. Och kanske fler.


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Measurement of the spin of the M87 black hole from its observed twisted light

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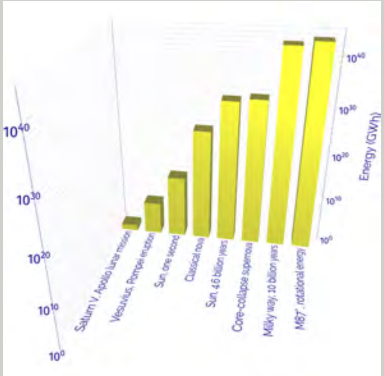
Accepted 2019 November 25. Received 2019 November 25; in original form 2019 July 2

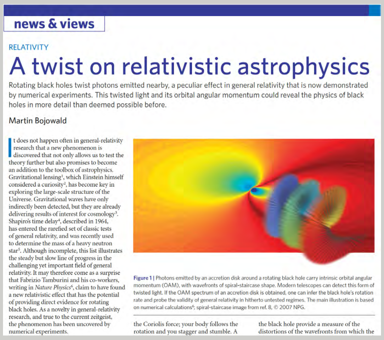
ABSTRACT
We present the first observational evidence that light propagating near a rotating black hole is twisted in phase and carries orbital angular momentum (OAM). This physical observable allows a direct measurement of the rotation of the black hole. We extracted the OAM spectra from the radio intensity data collected by the Event Horizon Telescope from around the black hole M87* by using wavefront reconstruction and phase recovery techniques and from the visibility amplitude and phase maps. This method is robust and complementary to black hole shadow circularity analyses. It shows that the M87* rotates clockwise with an estimated rotation parameter $a = 0.90 \pm 0.05$ with an ~ 95 per cent confidence level (c.l.) and an inclination $i = 17° \pm 2°$, equivalent to a magnetic arrested disc with an inclination $i = 163° \pm 2°$. From our analysis, we conclude that, within a 6σ c.l., the M87* is rotating.

Key words: black hole physics – gravitational lensing: strong – methods: data analysis – methods: numerical – techniques: image processing.

Titel och sammandrag av vår artikel i februari 2020 i *Monthly Notices of the Royal Astronomical Society: Letters* [4].



Jämförelse mellan olika observerade energier. Rotationsenergin hos M87* är den högsta som någonsin observerats i universum.


news & views

RELATIVITY

A twist on relativistic astrophysics

Rotating black holes twist photons emitted nearby, a peculiar effect in general relativity that is now demonstrated by numerical experiments. This twisted light and its orbital angular momentum could reveal the physics of black holes in more detail than deemed possible before.

Martin Bojowald

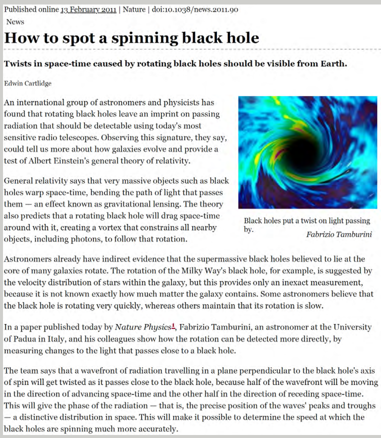
It does not happen often in general-relativity research that a new phenomenon is discovered that not only allows us to test the theory further but also promises to become an addition to the toolbox of astrophysics. Gravitational lensing[1], which Einstein himself considered a curiosity[2], has become key in exploring the large-scale structure of the Universe. Gravitational waves have only indirectly been detected, but they are already delivering results of interest for cosmology[3]. Shapiro's time delay[4], described in 1964, has entered the rarefied set of classic tests of general relativity, and was recently used to determine the mass of a heavy neutron star[5]. Although incomplete, this list illustrates the steady but slow line of progress in the challenging yet important field of general relativity. It may therefore come as a surprise that Fabrizio Tamburini and his co-workers, writing in *Nature Physics*[6], claim to have found a new relativistic effect that has the potential of providing direct evidence for rotating black holes. As a novelty in general-relativity research, and true to the current zeitgeist, the phenomenon has been uncovered by numerical experiments.

Figure 1 | Photons emitted by an accretion disk around a rotating black hole carry intrinsic orbital angular momentum (OAM), with wavefronts of spiral-staircase shape. Modern telescopes can detect this form of twisted light. If the OAM spectrum of an accretion disk is obtained, one can infer the black hole's rotation rate and probe the validity of general relativity in hitherto untested regimes. The main illustration is based on numerical calculations[6]; spiral-staircase image from ref. 8, © 2007 NPG.

the Coriolis force; your body follows the rotation and you stagger and stumble. A

the black hole provide a measure of the distortions of the wavefronts from which the

Ur en artikel i *Nature Physics* 2011 om vår OAM-metod för astronomi och dess bäring på astrofysik och svarta-hålforskning [5].


Published online 13 February 2011 | Nature | doi:10.1038/news.2011.90

News

How to spot a spinning black hole

Twists in space-time caused by rotating black holes should be visible from Earth.

Edwin Cartlidge

An international group of astronomers and physicists has found that rotating black holes leave an imprint on passing radiation that should be detectable using today's most sensitive radio telescopes. Observing this signature, they say, could tell us more about how galaxies evolve and provide a test of Albert Einstein's general theory of relativity.

General relativity says that very massive objects such as black holes warp space-time, bending the path of light that passes them — an effect known as gravitational lensing. The theory also predicts that a rotating black hole will drag space-time around with it, creating a vortex that constrains all nearby objects, including photons, to follow that rotation.

Black holes put a twist on light passing by. *Fabrizio Tamburini*

Astronomers already have indirect evidence that the supermassive black holes believed to lie at the core of many galaxies rotate. The rotation of the Milky Way's black hole, for example, is suggested by the velocity distribution of stars within the galaxy, but this provides only an inexact measurement, because it is not known exactly how much matter the galaxy contains. Some astronomers believe that the black hole is rotating very quickly, whereas others maintain that its rotation is slow.

In a paper published today by *Nature Physics*[1], Fabrizio Tamburini, an astronomer at the University of Padua in Italy, and his colleagues show how the rotation can be detected more directly, by measuring changes to the light that passes close to a black hole.

The team says that a wavefront of radiation travelling in a plane perpendicular to the black hole's axis of spin will get twisted as it passes close to the black hole, because half of the wavefront will be moving in the direction of advancing space-time and the other half in the direction of receding space-time. This will give the phase of the radiation — that is, the precise position of the waves' peaks and troughs — a distinctive distribution in space. This will make it possible to determine the speed at which the black holes are spinning much more accurately.

Ur en nyhetsartikel i *Nature* 2011 om vår *Nature Physics*-artikel [6].

§ https://eventhorizontelescope.org
¶ https://www.phys.psu.edu/people/mob6

Litteratur

[1] Martin Harwit. »Photon Orbital Angular Momentum in Astrophysics«. I: *The Astrophysical Journal* 597.2 (10 nov. 2003), s. 1266–1270. DOI: 10.1086/378623. URL: http://iopscience.iop.org/article/10.1086/378623/meta.

[2] Fabrizio Tamburini, Bo Thidé, Gabriel Molina-Terriza och Gabriele Anzolin. »Twisting of Light around Rotating Black Holes«. I: *Nature Physics* 7.3 (13 febr. 2011), s. 195–197. DOI: 10.1038/nphys1907. URL: http://www.nature.com/nphys/journal/v7/n3/abs/nphys1907.html.

[3] Roy P. Kerr. »Gravitational Field of a Spinning Mass as an Example of Algebraically Special Metrics«. I: *Physical Review Letters* 11.5 (1 sept. 1963), s. 237–238. DOI: 10.1103/PhysRevLett.11.237. URL: https://link.aps.org/doi/10.1103/PhysRevLett.11.237.

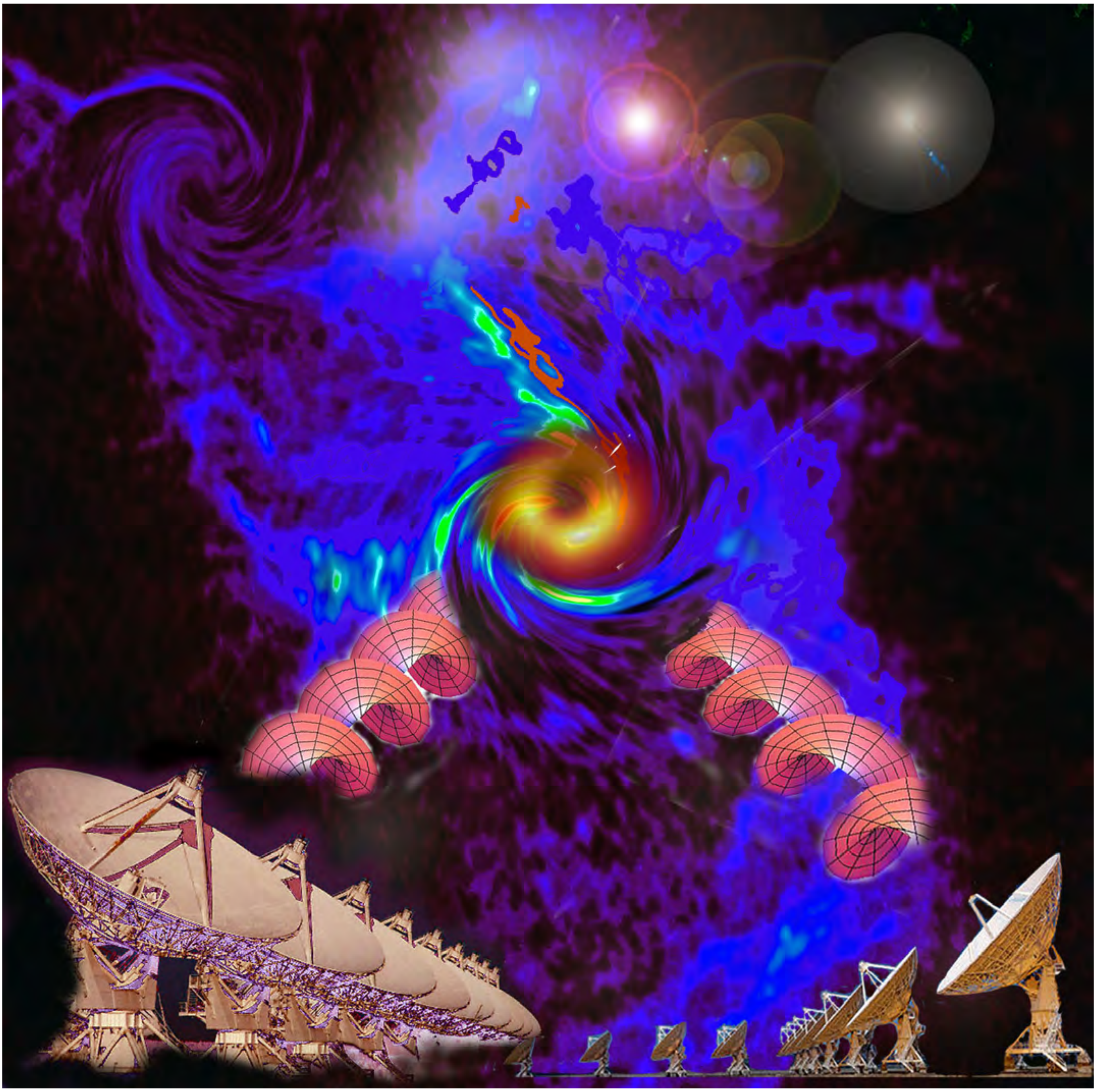
[4] Fabrizio Tamburini, Bo Thidé och Massimo Della Valle. »Measurement of the Spin of the M87 Black Hole from Its Observed Twisted Light«. I: *Monthly Notices of the Royal Astronomical Society: Letters* 492.1 (11 febr. 2020), s. L22–L27. DOI: 10.1093/mnrasl/slz176. URL: https://academic.oup.com/mnrasl/article/492/1/L22/5645245.

[5] Martin Bojowald. »Relativity: A Twist on Relativistic Astrophysics«. I: *Nature Physics* 7.3 (mars 2011), s. 188–189. DOI: 10.1038/nphys1938. URL: http://dx.doi.org/10.1038/nphys1938.

[6] Edwin Cartlidge. »How to Spot a Spinning Black Hole : Nature News«. I: *Nature* (13 febr. 2011). DOI: 10.1038/news.2011.90. URL: http://www.nature.com/news/2011/110213/full/news.2011.90.html.

[7] Giovanni Volpe. »Astronomical Twisters«. I: *Optics & Photonics Focus* 13 (Story 6 1 juni 2011). URL: http://opfocus.org/index.php?topic=story&v=13&s=6.

A 2011 article in *Optics & Photonics Focus* about our black-hole predictions, now confirmed, and our OAM research in general [7].



Figur 1 | Observering av radiostrålning med OAM utsänd från den omedelbara närheten av svarta hål. Förenklad skiss.

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LETTERS

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$$\hat{S}_z = \hbar \sum_{\sigma,\ell,p} \sigma \int_0^\infty \mathrm{d}k_0 \hat{a}^\dagger_{\sigma,\ell,p}(k_0) \hat{a}_{\sigma,\ell,p}(k_0)$$

Figur 3 | Inledningen av vår artikel i *Nature Physics* från februari 2011 där vi förutsade OAM i ljus/radio som emitteras nära ett roterande svart hål [2].

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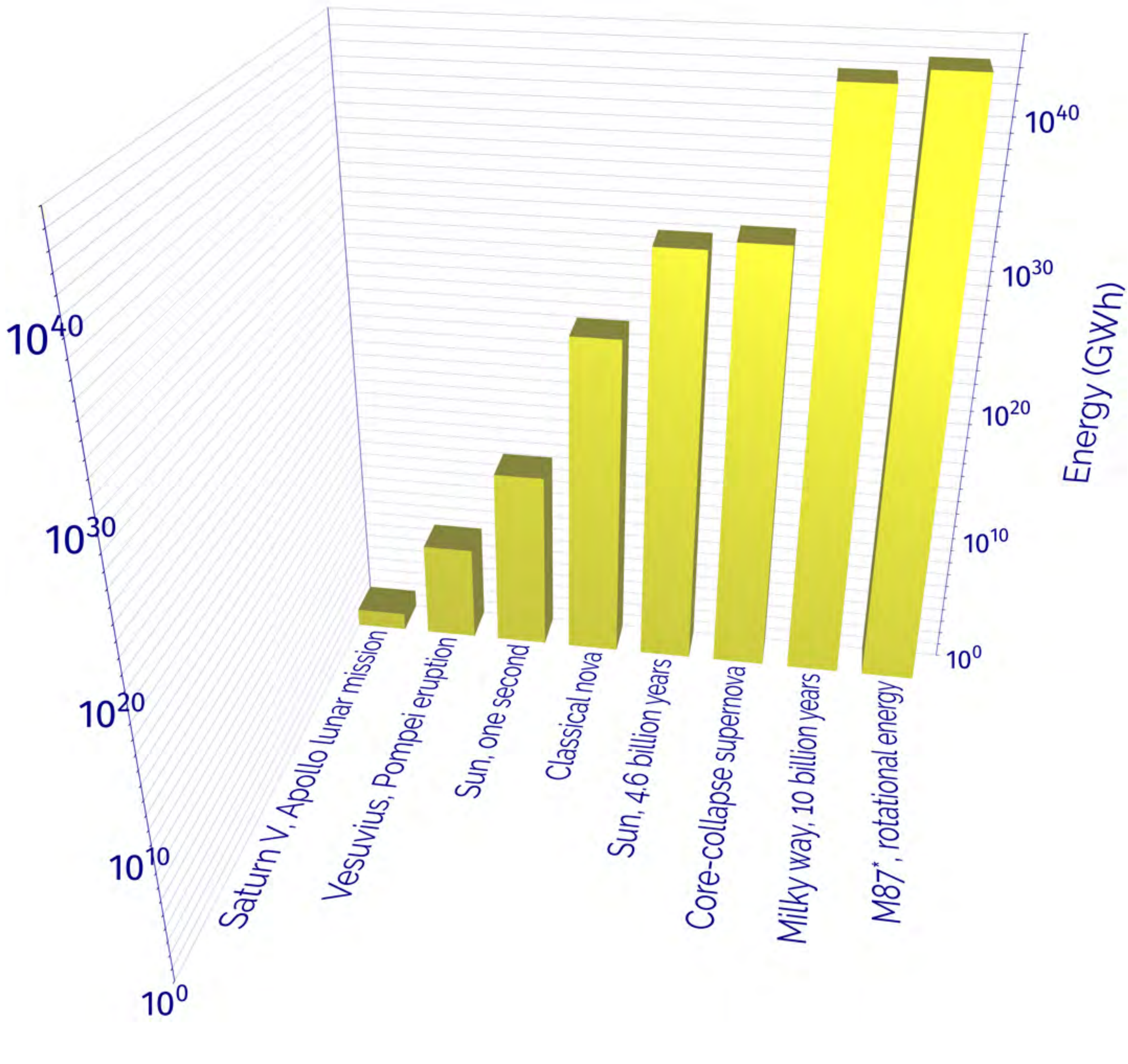
Figur 4 | Titel och sammandrag av vår artikel i februari 2020 i *Monthly Notices of the Royal Astronomical Society: Letters* [2].



Figur 5 | Jämförelse mellan olika observerade energier. Rotationsenergin hos M87* är den högsta som någonsin observerats i universum.

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Martin Bojowald

It does not happen often in general-relativity research that a new phenomenon is discovered that not only allows us to test the theory further but also promises to become an addition to the toolbox of astrophysics. Gravitational lensing[1], which Einstein himself considered a curiosity[2], has become key in exploring the large-scale structure of the Universe. Gravitational waves have only indirectly been detected, but they are already delivering results of interest for cosmology[3]. Shapiro's time delay[4], described in 1964, has entered the rarefied set of classic tests of general relativity, and was recently used to determine the mass of a heavy neutron star[5]. Although incomplete, this list illustrates the steady but slow line of progress in the challenging yet important field of general relativity. It may therefore come as a surprise that Fabrizio Tamburini and his co-workers, writing in *Nature Physics*[6], claim to have found a new relativistic effect that has the potential of providing direct evidence for rotating black holes. As a novelty in general-relativity research, and true to the current zeitgeist, the phenomenon has been uncovered by numerical experiments.

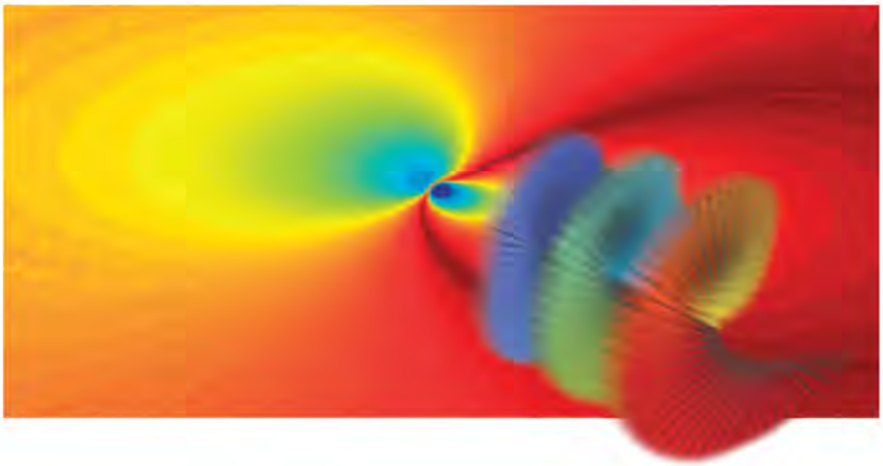

Figure 1 | Photons emitted by an accretion disk around a rotating black hole carry intrinsic orbital angular momentum (OAM), with wavefronts of spiral-staircase shape. Modern telescopes can detect this form of twisted light. If the OAM spectrum of an accretion disk is obtained, one can infer the black hole's rotation rate and probe the validity of general relativity in hitherto untested regimes. The main illustration is based on numerical calculations[6]; spiral-staircase image from ref. 8, © 2007 NPG.

the Coriolis force; your body follows the rotation and you stagger and stumble. A

the black hole provide a measure of the distortions of the wavefronts from which the

Figur 6 | Ur en artikel i *Nature Physics* 2011 om vår OAM-metod för astronomi och dess bäring på astrofysik och svarta-hålforskning [5].

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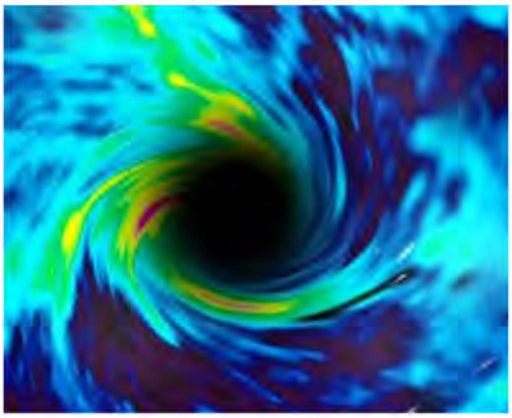
News

How to spot a spinning black hole

Twists in space-time caused by rotating black holes should be visible from Earth.

Edwin Cartlidge

An international group of astronomers and physicists has found that rotating black holes leave an imprint on passing radiation that should be detectable using today's most sensitive radio telescopes. Observing this signature, they say, could tell us more about how galaxies evolve and provide a test of Albert Einstein's general theory of relativity.



Black holes put a twist on light passing by. *Fabrizio Tamburini*

General relativity says that very massive objects such as black holes warp space-time, bending the path of light that passes them — an effect known as gravitational lensing. The theory also predicts that a rotating black hole will drag space-time around with it, creating a vortex that constrains all nearby objects, including photons, to follow that rotation.

Astronomers already have indirect evidence that the supermassive black holes believed to lie at the core of many galaxies rotate. The rotation of the Milky Way's black hole, for example, is suggested by the velocity distribution of stars within the galaxy, but this provides only an inexact measurement, because it is not known exactly how much matter the galaxy contains. Some astronomers believe that the black hole is rotating very quickly, whereas others maintain that its rotation is slow.

In a paper published today by *Nature Physics*[1], Fabrizio Tamburini, an astronomer at the University of Padua in Italy, and his colleagues show how the rotation can be detected more directly, by measuring changes to the light that passes close to a black hole.

The team says that a wavefront of radiation travelling in a plane perpendicular to the black hole's axis of spin will get twisted as it passes close to the black hole, because half of the wavefront will be moving in the direction of advancing space-time and the other half in the direction of receding space-time. This will give the phase of the radiation — that is, the precise position of the waves' peaks and troughs — a distinctive distribution in space. This will make it possible to determine the speed at which the black holes are spinning much more accurately.

Figur 7 | Ur en nyhetsartikel i *Nature* 2011 om vår *Nature Physics*-artikel [6].

optics & photonics focus

Astronomical Twisters

Black holes are enigmatic astronomical objects, which remain, as of yet, unobserved. We may, however, be in a position to trace their trail. It is possible that a rotating black hole imparts small twists to photons passing nearby, which we may be able to detect from Earth.

Black holes are one of the most intriguing predictions of Einstein's General Relativity Theory. These incredibly massive astronomical objects have yet to be seen; neither is there hope of ever seeing one, since nothing, not even light, can escape their huge gravitational attraction. Luckily, we can still hope to trace their trail. It is possible, for example, that a rotating black hole imparts small twists to the photons passing close by, and this should be detectable from Earth, providing, *en passant*, further evidence in favor of Einstein's General Relativity Theory. This is the proposal of an international group of researchers from the University of Padua (Italy), the Ångström Laboratory (Sweden), Macquarie University (Australia), and ICFO – the Institute of Photonic Sciences (Spain).

According to Einstein's General Relativity — a central cornerstone in our understanding of the Universe, with many scientific and technological implications — the presence of massive objects alters the fabric of space-time. An empty two-dimensional space-time, for example, can be visualized as a plastic piece of foil lying flat, which *wraps* where a mass, say an apple, is placed. We can detect the presence of such wrap by observing the motion of objects passing nearby: the trajectory of a marble will bend near the plastic foil wrap, and, analogously, the trajectory of a photon will bend near a space-time wrap. A black hole occurs when the curvature of the space-time is so large that not even something traveling at the speed of light, such as a photon, is able to escape; the space-time wrapping near a black hole has a distinctive structure and its fingerprint is transferred onto the radiation emitted nearby.

Black holes were first proposed in the 18th century by John Michell and Pierre-Simon Laplace, as objects whose gravitational force was so large as to retain even something capable of traveling at the speed of light. However, it was not until a century late that the advent of Einstein's General Relativity brought black holes onto solid theoretical ground: it was found that a black hole may be generated by the collapse of a star with a mass at least several times that of our Sun's. In 1963, Roy P. Kerr demonstrated that General Relativity also permitted the existence of rotating black holes [1].

However, how could we possibly detect the presence of a rotating black hole? "We went back to an idea put forward by Enrico Fermi," explains Fabrizio Tamburini from the University of Padua, "in which he considered how a rotating gravitational lens produced an effect on the light passing nearby." "From Einstein's General Relativity," adds Bo Thidé from the Swedish Institute of Space Physics at the Ångström Laboratory, "any rotating massive body drags with it space and time, a phenomenon known as *frame dragging*.

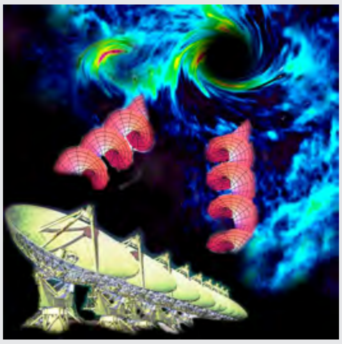


Figure 1: Detecting the twist of a black hole. The light emitted near a rotating black hole acquires a characteristic orbital angular momentum, which may be detected from Earth by using an appropriate set of radio telescope arrays and data analysis techniques. Figure courtesy: Fabrizio Tamburini, University of Padua.

This should induce a twist, known as orbital *angular momentum*, on a nearby passing light beam. This effect should be particularly evident around a massive rotating black hole." In our simile, if a plastic foil (the space-time) is dragged by an apple (the rotating black hole) spinning on it, it will acquire a characteristic twist, which can be transferred onto a marble (a photon) passing nearby.

Orbital angular momentum (OAM) is one of the properties of photons, as is their wavelength or their color [2]. Unlike wavelength and color, however, OAM has not been exploited by astronomers until now. "In 2003, Martin Harwit [3] wrote a provocative paper saying that astronomers use light, but only a minimal part of it," remarks Tamburini. "In particular, they don't take advantage of its orbital angular momentum." In 2007, Thidé proved mathematically that with a certain antenna one can generate or detect beams carrying OAM at radio frequencies [4] and he started to look for an astronomical phenomenon that would induce a significant amount of OAM to make it detectable. "I went

to various universities and institutes presenting this work," recalls Thidé, "until we came up with the idea of looking at the light generated near the space-time wrap of a rotating black hole."

Studying the solution to the equations of General Relativity in the proximity of a rotating black hole, they found that some light generated nearby would indeed acquire some OAM — enough for it to be detectable from Earth. "We solved the equation of General Relativity using a powerful computational technique, which permitted a very fast solution, and could even be done on a laptop," explains Tamburini. "We carried out an optics experiment using a rotating black hole."

The next natural step will be to try to detect OAM in astronomical signals. "We are looking into the possibility of using the Very Large Array (VLA) telescope in New Mexico (USA), or the Atacama Large Millimeter Array (ALMA) telescope in Chile, to do this measurement," explains Thidé, "but maybe data containing this information already exists, since several telescopes have observed the radiation generated from the regions surrounding black holes. Except that no one, to date, has specifically looked for the OAM.

A success in detecting the signature of OAM in the radiation coming from the proximity of a rotating black hole would not only be strong evidence for the existence of black holes, but it would also provide a strong confirmation of the validity of Einstein's General Relativity. "The real novelty of our result is that we found a new effect owing to General Relativity, namely that the electromagnetic radiation emitted near a black hole, an enormously massive rotating object, carries with itself information about the local wrapping of space," observes Thidé. "By measuring the phase map of the OAM we can now test Einstein's General Relativity using radio telescopes. This is what we are most proud of."

[1] R. P. Kerr, *Gravitational Field of a Spinning Mass as an Example of Algebraically Special Metrics*, Phys. Rev. Lett. **11**, 237–238, 1963.

[2] G. Molina-Terrizza, J. P. Torres & L. Torner, *Twisted Photons*, Nat. Phys. **3**, 305-310, 2007.

[3] M. Harwit, *Photon Orbital Angular Momentum in Astrophysics*, Astrophys. J. **597**, 1266–1270, 2003.

[4] B. Thidé *et al.*, *Utilization of Photon Orbital Angular Momentum in the Low-Frequency Radio Domain*, Phys. Rev. Lett. **99**, 087701, 2007.

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Fabrizio Tamburini, Bo Thidé, Gabriel Molina-Terriza & Gabriele Anzolin, **Twisting of light around rotating black holes**, Nature Physics (2011) **7**, 195-197.