Image courtesy of ESA / AOES Medialab

Image courtesy of ESA / XMM-Newton (X-rays); ESA / Herschel / PACS / SPIRE / CD Wilson, McMaster University, Hamilton, Ontario, Canada (far-infrared and sub-millimetre)

Image courtesy of NASA / JPL-Caltech / D Gouliermis (Max-Planck Institute for Astronomy, Heidelberg, Germany) and ESA

More than meets the eye: the exotic, high-energy Universe

In the third article in this series on astronomy and the electromagnetic spectrum, learn about the exotic and powerful cosmic phenomena that astronomers investigate with X-ray and gamma-ray observatories, including the European Space Agency's XMM-Newton and INTEGRAL missions.

By Claudia Mignone and Rebecca Barnes

In the 1960s, the advent of the space age initiated the era of high-energy astronomy. For the first time, astronomers could see the Universe with X-ray and gamma-ray eyes. Electromagnetic (EM) radiation at these wavelengths is emitted by cosmic sources with extreme properties such as exceptionally high temperatures, extraordinarily high densities or remarkably strong magnetic fields. Ground-based observatories, however, had been unable to register these rays, which have wavelengths too short to penetrate Earth's atmosphere (figure 1). It took the first space observatories to unveil this turbulent and ever-changing Universe.

In just half a century, observations made at the highest energies have significantly changed our view of the cosmos. By studying the X-ray and gamma-ray sky, astronomers have discovered several new types of astronomical sources and have enhanced their knowledge of many other types of objects. To examine the Universe in this range of the EM spectrum[w1], the European Space Agency (ESA; see box) operates two missions: the XMM-Newton (X-rays) and INTEGRAL (X-rays and gamma rays) space observatories. The techniques used in X-ray and gamma-ray astronomy and by these two missions were introduced in the second article in this series (Mignone & Barnes, 2011b); this article provides an overview of what these missions have taught us, from the life of stars to the structure of the Universe. For an overview of the EM spectrum and its role in astronomy, see the first article in this series (Mignone & Barnes, 2011a).

Unveiling the birth and death of stars

Stars are born when gravity causes huge clouds of gas and dust to collapse, fragment and form protostars. These protostars later grow into fully fledged stars when nuclear fusion ignites in their cores. How a star then continues to evolve depends on its mass, with massive stars destined to a shorter life and a more spectacular demise than their lower-mass counterparts (figure 2).

It is the early and late stages of

REVIEW

- Physics
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This article, the third in a series, describes European research activities within the field of high-energy astronomy. The second article in the series described the techniques used by two ESA missions, XMM-Newton (X-rays) and INTEGRAL (X-rays and gamma rays); this article describes some of their results, including insights into the birth and death of stars, as well as the more distant Universe.

For older students (16+), the article is ideal for physics lessons, where it could be used to address astrophysics (the life of stars, cosmic objects, the Big Bang theory), optics or even quantum physics (spectral ranges, relationship between wavelength and energy, EM waves), mass and gravity. It could also be used in geography lessons about the Universe, solar systems and cosmic objects.

To make it accessible to younger students (age of 10-15 years) as well, I would suggest the teacher selects just parts of the article to discuss.

The article could be very useful in English lessons too, or – once it has been translated – in German, French or other language lessons. Because the article is not too technical, even teachers who are not very familiar with physics could use it.

The article could also be used to stimulate discussion, with questions including:

1. Describe the European Space missions XMM-Newton and Integral.
2. Give an overview of the electromagnetic spectrum (including visible, infrared and UV).
3. What is the relationship between wavelength, energy and frequency?
4. Why do we use space observatories in addition to ground-based observatories?
5. Why are gamma rays emitted by hotter sources than X-rays?
6. What are X-ray binaries?
7. What can happen to massive stars at the ends of their lives?

Gerd Vogt, Higher Secondary School for Environment and Economics, Yspertal, Austria

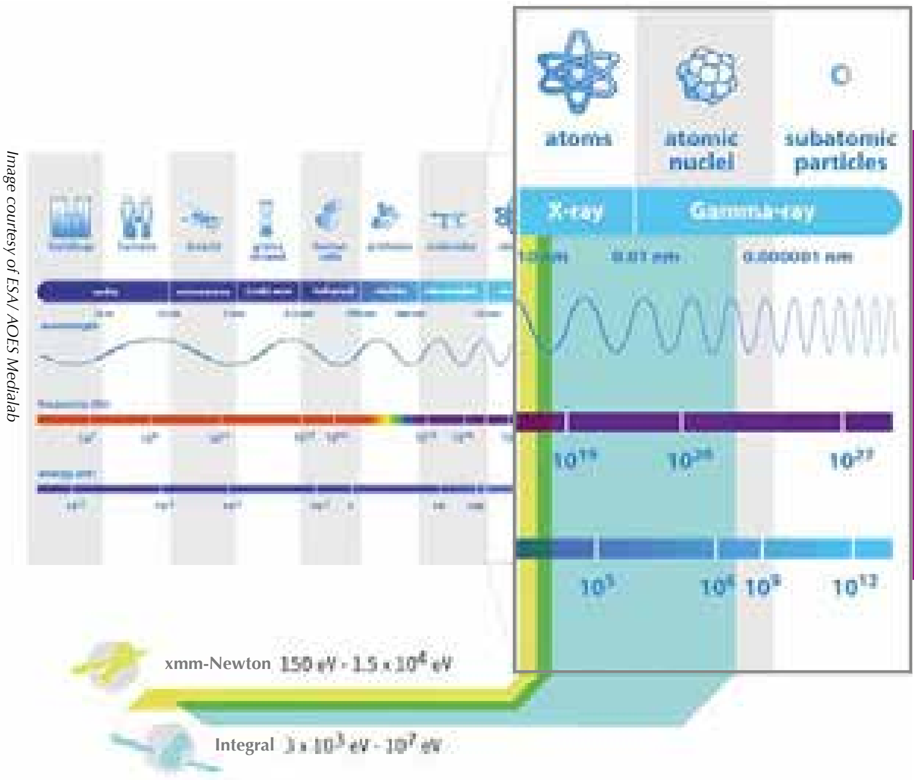

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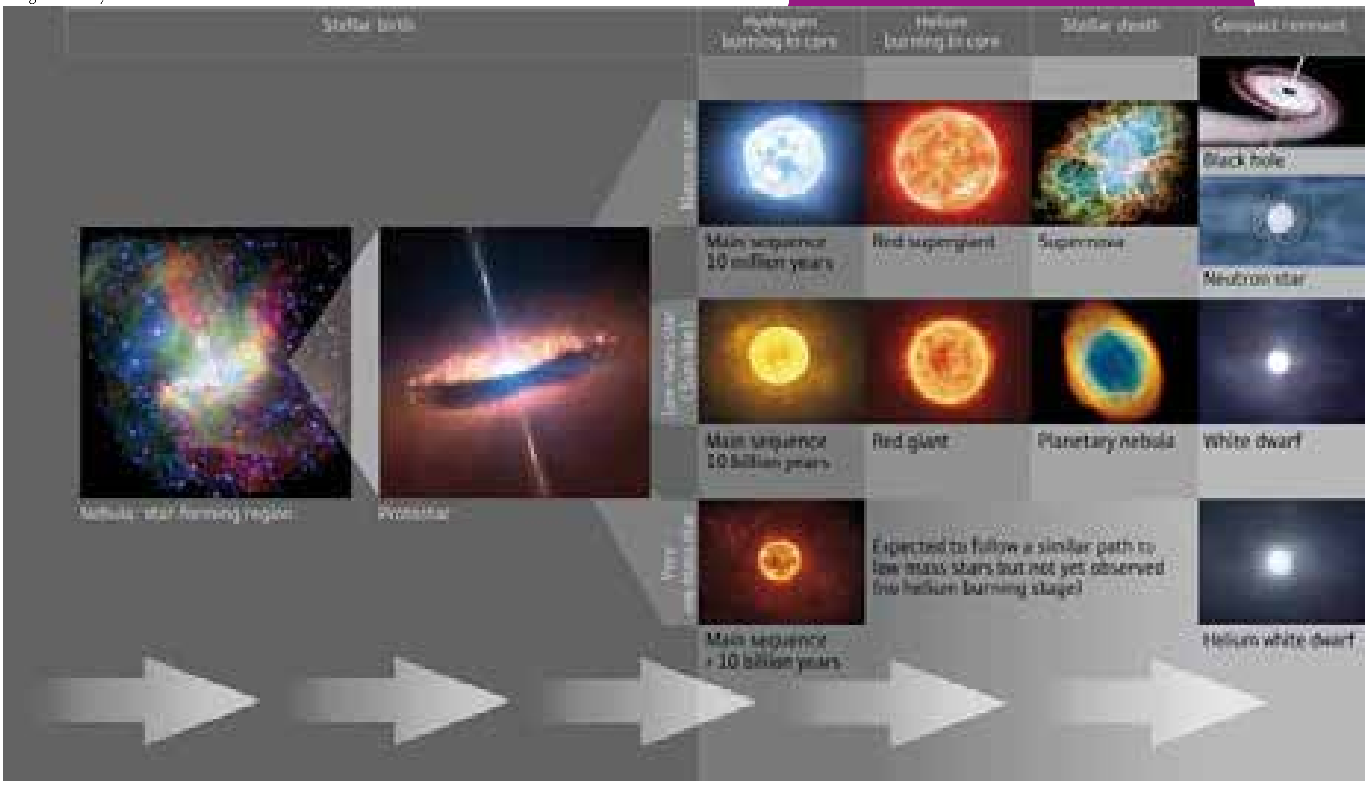
Figure 1: The EM spectrum, with the high-energy regions observed by ESA's XMM-Newton and INTEGRAL space observatories highlighted. X-rays are emitted by cosmic sources at millions of degrees Celsius; gamma rays by sources at hundreds of millions of degrees Celsius. XMM-Newton detects X-rays at energies of 150-1.5 x 10^4 eV, whereas INTEGRAL detects both X-rays at energies of 3 x 10^3-3.5 x 10^4 eV and gamma rays at 1.5 x 10^4 keV – 1.0 x 10^7 keV

Figure 2: The life cycle of stars

Image courtesy of ESA / AOES Medialab



a star's life cycle that are the most interesting for X-ray and gamma-ray astronomers. Because some very young stars shine brightly under X-rays, astronomers can detect many of them by looking at star-forming regions with X-ray telescopes such as XMM-Newton (figure 3). The most massive young stars release highly energetic radiation and extremely hot gas, which are observed at X-ray wavelengths and influence how other stars form in the surrounding area. Astronomers using XMM-Newton have detected bubbles of hot gas from young massive stars in many regions of the sky[w2], including the Orion Nebula and the star-forming region NGC 346. This research feeds into our understanding of how young massive stars affect star formation around them – a hot topic in modern astrophysics.

Image courtesy of NASA / JPL-Caltech / D Gouliermis (Max-Planck Institute for Astronomy, Heidelberg, Germany) and ESA

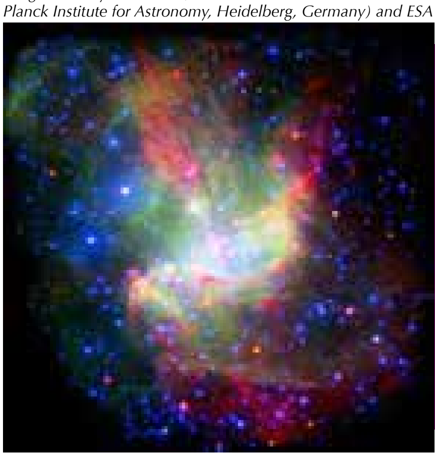


Figure 3: The star-forming region NGC 346 is located in the Small Magellanic Cloud, one of the Milky Way's neighbouring galaxies. This false-colour image combines observations performed with XMM-Newton in X-rays (blue) with data gathered in visible (green) and infrared (red) light with the Hubble and Spitzer space telescopes, respectively

At the ends of their lives, massive stars explode as supernovae (as described in Székely & Benedekfi, 2007), heating the surrounding gas to extremely high temperatures and accelerating particles, such as electrons, to very high speeds. As a result, an abundance of X-rays and gamma rays are released (figure 4). Furthermore, many elements heavier than iron, such as lead, nickel and gold, are synthesised during supernova explosions (to learn more, see Rebusco et al., 2007). Some of these elements are radioactive and eventually decay into stable isotopes, producing gamma rays in the process. Astronomers using INTEGRAL have surveyed the Milky Way and found traces of the radioactive isotope aluminium-26. Just like archaeologists, they have delved into the history of our galaxy and performed a census of past supernovae. The results demonstrate that, in the Milky Way, supernovae occur on average once every 50 years[w3].

After a supernova explosion, all that remains of the massive star is an extremely compact and dense object – either a neutron star or a black hole. With such a huge mass squeezed into a restricted space, these remnants have exceptionally strong gravitational fields and exert an intense pull on nearby matter, but they are fairly difficult to detect. However, if the

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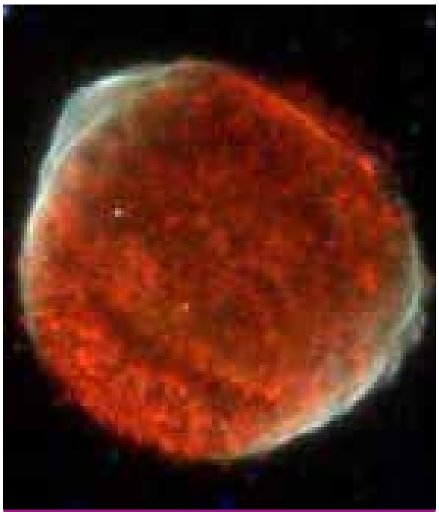

Figure 4: X-ray image of the supernova remnant SN 1006 as viewed with XMM-Newton. This object is the remains of a supernova that was seen by Chinese astronomers in 1006 AD. Visible in the upper-left and lower-right corners are shock waves where particles such as electrons are accelerated to very high speeds

Image courtesy of ESA / AOES Medialab

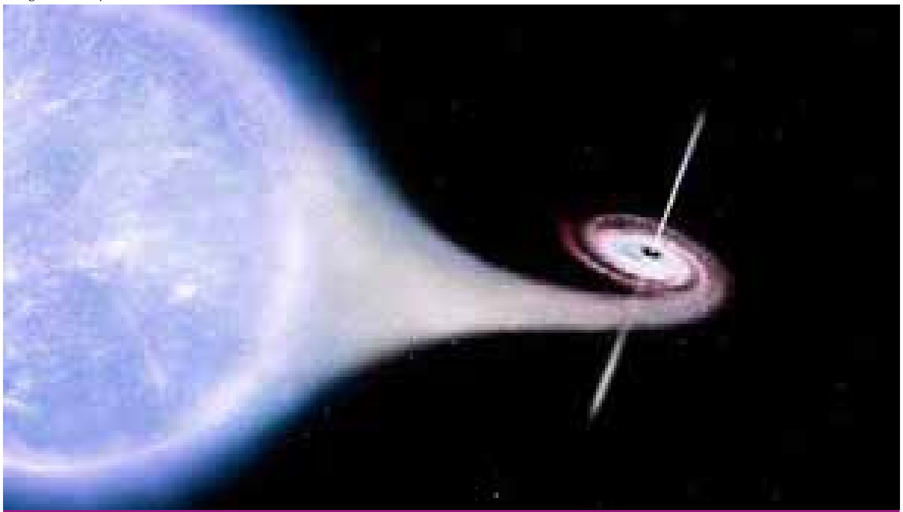

Figure 5: Artist's impression of an X-ray binary. With its intense gravitational field the black hole on the right draws matter from its companion, a blue super-giant star, on the left. The stripped material spirals around the black hole, forming an accretion disc, which shines brightly at the highest energies. Two powerful jets of highly energetic particles stem from the vicinity of the black hole

neutron star or black hole is part of a binary stellar system (two stars orbiting around a common centre of mass), it may start devouring matter from its companion star; the accreting matter then heats up to millions of degrees, emitting X-rays and gamma rays. This high-energy emission can be used to reveal the presence of a neutron star or black hole.

These systems are called X-ray binaries (figure 5) and were discovered in the late 1960s via X-ray observations. Back then, neutron stars and black holes had only been predicted by theory, so these observations provided the first proof of their existence. Since then, several generations of space-based observatories have helped astronomers to learn more. XMM-Newton and INTEGRAL have studied many X-ray binaries (which may also release gamma rays), revealing important details about the physics of black holes and neutron stars. For example, gamma rays from Cygnus X-1, observed using INTEGRAL[w4], helped astronomers to better understand how matter is accreted via a disc onto this black hole and partly expelled in two symmetric jets.

The distant Universe

High-energy astronomers not only observe the birth and death of stars within the Milky Way and nearby galaxies, but also use X-rays and gamma-rays to investigate the much more distant Universe – including super-massive black holes and clusters of galaxies.

All large galaxies harbour super-massive black holes at their cores, with masses a few million to a few billion times that of the Sun. Some galaxies, known as *active galaxies*, contain super-massive black holes that, unlike the one in the centre of the Milky Way, are active. Devouring matter from their surroundings, these black holes release high-energy radiation as well as powerful jets of highly energetic particles (figure 6). ESA's XMM-Newton and INTEGRAL are thus ideal tools to hunt for active galaxies and to investigate the mechanisms that power them. Astronomers cannot see all the necessary details in more distant high-energy sources, so they also collect data from as many nearby active galaxies as possible. By combining data from close and distant galaxies, astronomers have figured out how super-massive black holes accrete matter via a disc, and how these discs may be surrounded by absorbing clouds of gas[w5].

On a still larger scale, galaxies tend to assemble in clusters of up to several thousand galaxies. These clusters are the largest structures in the Universe to be held together by gravity, and release a diffuse X-ray glow. This glow, first observed in the 1970s, revealed that the intergalactic space in a cluster contains an enormous amount of hot gas. Together with other observatories that probe the sky across the EM spectrum, XMM-Newton has observed hundreds of galaxy clusters (figure 7).

Image courtesy of ESA / XMM-Newton (X-rays); ESA / Herschel / PACS / SPIRE / CD Wilson, McMaster University, Hamilton, Ontario, Canada (far-infrared and sub-millimetre)

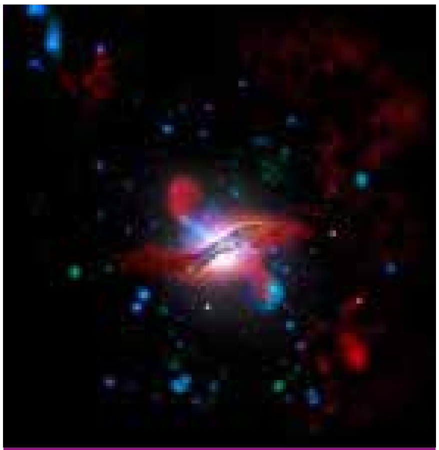

Figure 6: The nearby active galaxy Centaurus A (NGC 5128). This false-colour image combines observations performed with XMM-Newton in X-rays (cyan, blue and purple, in order of increasing energy) and data gathered at longer, far-infrared (yellow) and sub-millimetre (red) wavelengths using ESA's Herschel Space Observatory. At X-ray wavelengths, a number of foreground point-like sources are visible: these are X-ray binaries belonging to our galaxy, the Milky Way

Image courtesy of ESA / ESO / Subaru / R Gobat et al.

Figure 7: Observations of the very distant galaxy cluster CL J1449+0856 performed in X-rays (purple glow) with XMM-Newton are superimposed onto an image taken with ground-based telescopes at near-infrared wavelengths. Most objects visible in the image are very faint and distant galaxies. The galaxies belonging to the galaxy cluster are visible as a clump of faint, red objects. With a temperature above 20 million Kelvin, the hot gas pervading the intergalactic space shines brightly in X-rays

Image courtesy of NASA / ESA / R Massey (California Institute of Technology)

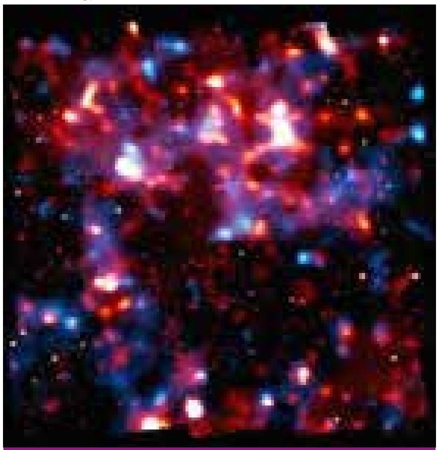

Figure 8: This map compares the distribution of 'normal' matter, traced via hot gas seen by XMM-Newton (in red) and stars and galaxies observed with the Hubble Space Telescope (in grey), to the distribution of the invisible dark matter (in blue), which has been inferred from the gravitational lensing effect. The map demonstrates how 'normal' matter across the Universe follows the structure of an underlying 'scaffolding' of dark matter

Physics

These include a very distant cluster that is one of the earliest structures to have formed in the Universe[w6], just 3 billion years after the Big Bang. This may sound like a very long time, but it is less than one quarter of the Universe's present age.

Galaxy clusters are located in the densest knots of the cosmic web, the gigantic network of structure that makes up the Universe and consists mostly of invisible dark matter[w7]. Using XMM-Newton, astronomers have spotted matter where it is most densely concentrated, thus tracing the distribution of cosmic structure across the Universe (figure 8).

From the birth of a star to the structure of the Universe – what next? X-ray and gamma-ray observatories, including ESA's XMM-Newton and INTEGRAL, continue to keep a close watch on the ever-changing, high-energy sky, recording sudden violent outbursts of X-rays and gamma-rays. By continuing to unveil celestial wonders to astronomers, these remarkable space observatories are helping to solve the mysteries of our Universe.

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Székely P, Benedekfi Ö (2007) Fusion in the Universe: when a giant star dies.... *Science in School* **6**: 64-68. www.scienceinschool.org/2007/issue6/fusion

Web references

w1 – To learn more about X-ray and gamma-ray astronomy at ESA, watch Rebecca Barnes in Episode 5 of the Science@ESA vodcast: *The untamed, violent Universe.* See the ESA Science and Technology website (http://sci.esa.int/vodcast) or use the direct link http://tinyurl.com/esaepisode5

w2 – Find out more about how XMM-Newton helped in studying the star-forming region NGC 346 and detected a hot-gas bubble in the Orion Nebula. See www.esa.int/science and http://sci.esa.int/xmm-newton

respectively, or use the direct links http://tinyurl.com/7xo9qez (NGC 346) and http://tinyurl.com/28d8ac (Orion)

w3 – Learn how INTEGRAL identified the supernova rate for the Milky Way and how XMM-Newton helped to analyse the remnants of the Tycho supernova. See www.esa.int/science or use the direct links http://tinyurl.com/72mhz4s (Milky Way) and http://tinyurl.com/752zbh6 (Tycho)

w4 – The ESA website has more information about X-ray binaries.

Find out how gamma rays from the Cygnus X-1 jets were observed with INTEGRAL ('Integral spots matter a millisecond from doom'). See www.esa.int/science or use the direct link http://tinyurl.com/6sxhlqx

Learn about how Supergiant Fast X-ray Transients were observed by XMM-Newton ('Neutron star caught feasting on clump of stellar matter'). See http://sci.esa.int/xmm-newton or use the direct link http://tinyurl.com/7caahph

w5 – Read more details of ESA's findings about active galaxies. See http://sci.esa.int/xmm-newton (XMM-Newton) and http://sci.esa.int/integral (INTEGRAL) or use the direct links http://tinyurl.com/om5sar and http://tinyurl.com/3rfws48

w6 – Read about how XMM-Newton helped discover an old galaxy cluster in the young Universe. See http://sci.esa.int/xmm-newton or use the direct link: http://tinyurl.com/5vcf3wz

w7 – Learn about the first 3D map of the Universe's dark matter scaffolding. See: www.esa.int or use the direct link: http://tinyurl.com/8r3gw7c

w8 – For more information on the European Space Agency, visit the ESA website (www.esa.int).

w9 – Find out more about EIROforum. See: www.eiroforum.org

Resources

ESA has produced many more education materials. See: www.esa.int/educationmaterials

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The European Space Agency (ESA)[w8] is Europe's gateway to space, organising programmes to find out more about Earth, its immediate space environment, our Solar System and the Universe, as well as to co-operate in the human exploration of space, to develop satellite-based technologies and services, and to promote European industries.

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