Catch me if you can:

How the fastest ejecta light up a neutron star merger in the ultraviolet

When two neutron stars collide, they eject neutron-rich matter into space. In most of this outflow, the heaviest elements in the cosmos are forged by the so-called "rapid neutron capture process", and the subsequent decay of these freshly formed elements gives rise to an optical flash called a kilonova. In the fastest portions of the ejecta, free neutrons can avoid being captured by nuclei, and their decay produces a blue flash about 30 minutes after the collision. A new study led by Lukas Schnabel, a PhD student at the Hamburg Observatory, shows that such a flash could be detected by the ULTRASAT satellite out to large distances. The findings were recently published in the *Monthly Notices of the Royal Astronomical Society*.

Where the heaviest elements are made

A neutron star (NS) has 1.4 times the mass of the Sun, packed into a sphere roughly 24 kilometres across. When two of these NSs exist in a binary system, they can slowly spiral inwards as their orbit loses angular momentum and energy through gravitational-wave emission. Once they collide, neutron-rich matter is ejected into space at high velocities. In less than a second, these neutrons are captured by atomic nuclei in a process called the rapid neutron-capture process (r-process). The nuclei then grow into heavy elements such as gold, platinum, or uranium. Most of the newly formed nuclei are highly radioactive. Their decay heats the ejected gas, which glows in the optical and infrared for days as a so-called kilonova.

The fastest debris

While, on average, the ejecta expands at about 20–30 % of the speed of light, full general-relativistic simulations have found small amounts of much faster debris. Part of it is sprayed out at the contact surface between the two stars. More follows when the core of the merged object is compressed and bounces back. These layers can reach more than 60 % of the speed of light and they thin out so rapidly that the neutrons have not much time to find a nucleus. It had been suggested earlier that neutrons could survive nucleosynthesis in this way, and our goal was to find out whether and under which conditions this happens.

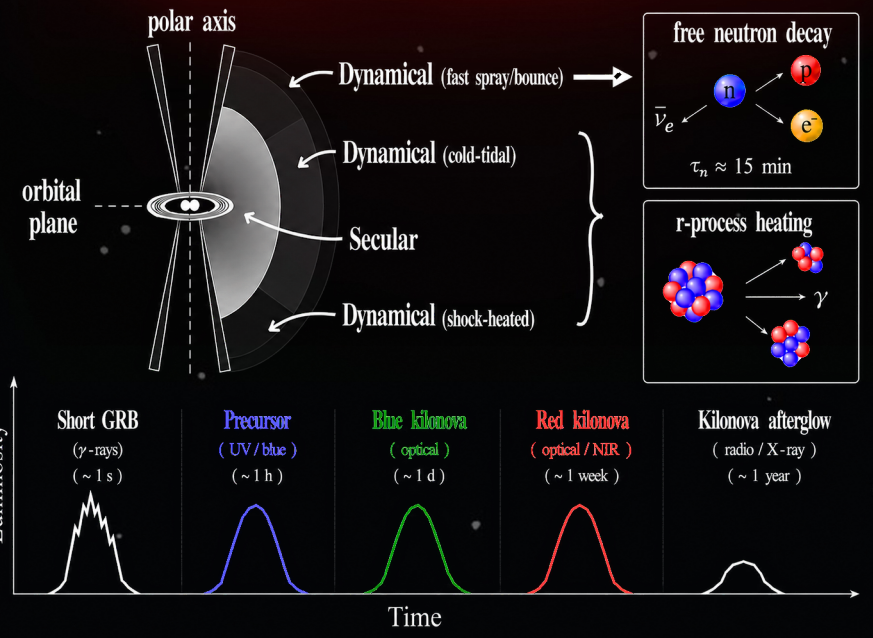


Figure 1. *Schematic overview of the ejecta of a neutron star merger (top, not to scale) and the resulting electromagnetic signals (bottom). The fastest dynamical ejecta are mainly heated by the decay of free neutrons, which have a mean lifetime of about 15 minutes. The slower ejecta are heated by the radioactive decay of r-process nuclei. The heating by free neutrons produces a UV/blue precursor about one hour after the merger, before the kilonova.*

Where neutrons avoid being caught

We calculated the nuclear reactions for many thousands of different outflows, varying the expansion velocity, the strength of the heating, and the neutron-richness of the outflow. In most cases, nearly all neutrons end up inside nuclei. At high speeds, and especially in very hot or very neutron-rich gas, a large fraction of them is left over (Figure 2). We also found a simple analytic formula that accurately predicts which of the two cases occurs.

In the outermost and fastest-moving layers, neutrons can remain free. These neutrons decay after about 15 minutes into protons, electrons and electron-type anti-neutrinos. If they account for only five percent of the ejecta mass, their decay becomes the dominant source of heating during the first few hours after the merger.

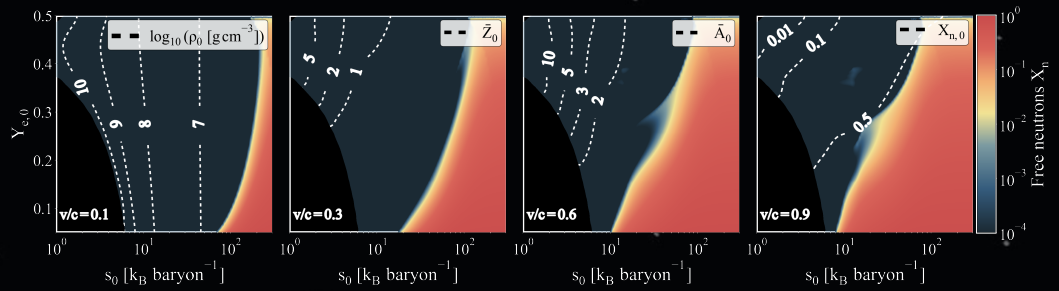


Figure 2. *Fraction of free neutrons one minute after the merger for a large set of model outflows. The four panels correspond to expansion velocities of 10, 30, 60 and 90 percent of the speed of light. The horizontal axis shows how strongly the matter was heated (entropy), the vertical axis its proton fraction. In the red regions, a large fraction of the neutrons remains free. This region grows with increasing velocity.*

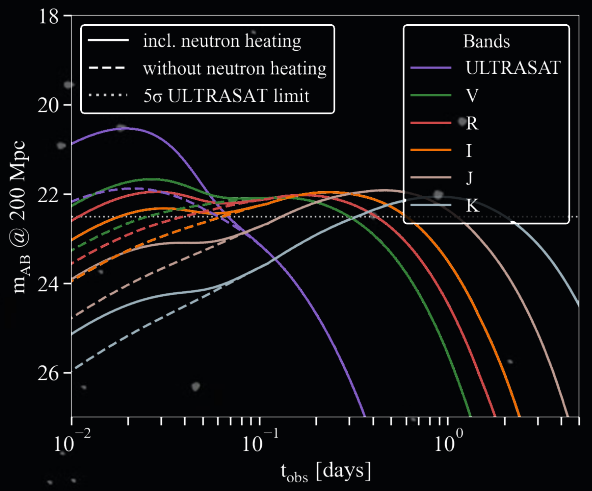


Figure 3. *Predicted light curves of a neutron star merger at a distance of 652 million light-years, with (solid) and without (dashed) heating by free neutrons. In the ULTRASAT band (purple), the emission peaks after about 30 minutes above the detection limit (dotted line).*

A source for ULTRASAT?

How bright can such neutron-powered kilonova precursors become (Figure 3)? Free-neutron heating makes the outer layer about ten times brighter during the first hour, with most of the emission in the ultraviolet. The emission peaks after about 30 minutes, while the kilonova itself reaches its maximum roughly a day later.

Only a tiny amount of free neutrons ($\sim 10^{-6} M_\odot$) is needed for ULTRASAT to be able to detect the signal from mergers up to about 650 million light years away. This is close to the distance at which the gravitational-wave detectors of the LIGO-Virgo-KAGRA collaboration are expected to find neutron star mergers in their next observing run.

Since free neutrons survive over a wide range of conditions, we expect such precursors to be a common feature of neutron star mergers. How bright they are depends on the details of the system and the conditions in the ejecta. Binaries with very unequal masses, mergers involving a rapidly spinning neutron star and neutron star black hole mergers eject large amounts of cold, neutron-rich matter and should produce particularly bright precursors. The speed of the fastest ejecta, in turn, carries the imprint of matter at supra-nuclear densities. An observed precursor could therefore help to constrain the properties of the densest form of matter in today's Universe.

PUBLICATION

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SUMMARY

In the fastest ejecta of neutron star mergers, a substantial fraction of the neutrons is not captured by nuclei. Their decay can power an ultraviolet precursor about half an hour after the merger, which ULTRASAT can detect out to about 652 million light-years.

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