PROCEEDINGS OF SCIENCE

SN 2023ixf: the multi-messenger observations

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SN 2023ixf is one of the closest core collapse supernovae in the last decades. The object has attracted a large interest in the astronomical community and has been investigated over the whole electromagnetic spectrum and in the neutrino and gravitational domains. This paper will briefly review the multimessenger observations of SN 2023ixf.

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1. Introduction

SN 2023ixf was discovered by [24] on 2023 May 19 at a clear magnitude of 14.9 in the host galaxy M101, a spiral galaxy at a distance of about 6.7 Mpc. SN 2023ixf was classified as a type II supernova a few hours after the discovery [48]. The supernova attracted large attention in the astronomical community, being one of the closest supernovae in the last decade. The observations of SN 2023ixf have been performed in the optical, infrared and ultraviolet domains, but also with X-rays and gamma rays, neutrinos, gravitational waves, making it a multi-messenger target. To date, several tens papers about SN 2023ixf have been published. The present review concisely summarizes the multi-messenger investigations of SN 2023ixf.

2. Optical, infrared and radio observations

SN 2023ixf was the target of an extensive photometric coverage over a broad range of photometric bands. The multi-color light curve is shown in Fig. 1, where the detections in the radio and X-ray domains described in the next sections are marked, together with the search windows used for the upper limitsny Fermi-LAT, SuperKamiokande, IceCube.

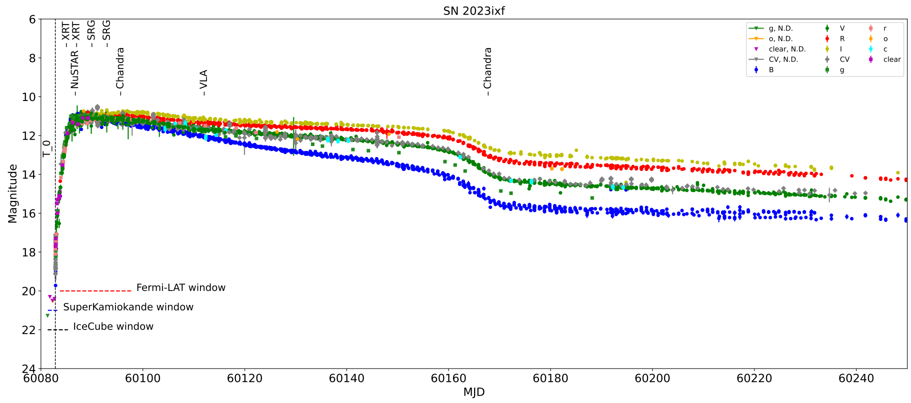

Figure 1: The early photometric evolution of SN 2023ixf in different bands: B, V, R, I, o, c, g, r, CV, clear; data from ATLAS, AAVSO, circulars and telegrams, N.D. marks non detections.

The light curve is consistent with the class of SN II, showing a rise to a maximum in about five days, followed by a plateau lasting for about four weeks, a short term fast decline and a later slow decline [19, 20, 26, 34, 37, 54, 60, 63, 67, 70].

The early optical spectroscopic observations showed the flash ionization features of hydrogen, helium, carbon, nitrogen, while the early UV spectra showed the presence of highly ionized C, N, O, Si, Fe with narrow absorptions and broad emissions (Fig. 2). The observed temperature increase could not be explained by shock cooling alone, suggesting a delayed shock breakout in a dense CircumStellar Medium (CSM) [4–8, 10, 12, 15, 17, 19–23, 26, 27, 29, 31–34, 37, 39, 40, 42, 46, 49–52, 57, 58, 60, 64–70]. An asymmetric explosion has been suggested [13, 55–57, 65, 65].

Millimeter observations of SN 2023ixf from day 2 to day 18 after the explosion did not detect any signal [4], as the LOFAR observations in the first year [62]. On the other hand, SN 2023ixf was detected 29 days after the explosion with the VLA [38] and 152.3, 206 and 269 days after the explosion at 6.9 and 8.4 GHz [25].

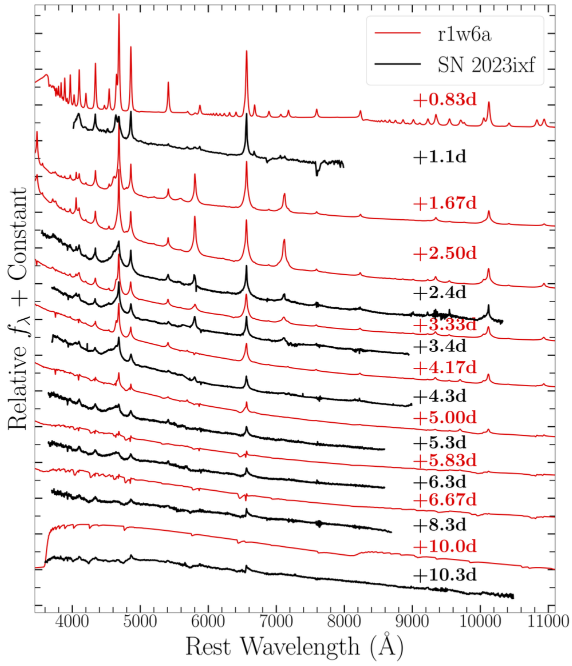

Figure 2: Optical spectroscopic observations during the first days after explosion [26]. Image credits: https://www.wynnjacobsongalan.com/research

3. The Progenitor

A large set of M101 pre-discovery imaging observations from ground-based telescopes, HST and Spitzer Space Telescope suggest the nature of the SN 2023ixf progenitor to be a dusty and variable red supergiant, with an estimated mass ranging from 8 to 20 $M_\odot$ [11, 13, 14, 19, 28, 40, 45, 46, 49, 51, 59, 64, 66].

The circumstellar medium could have been produced by an enhancement in the mass loss before the SN explosion, but several archival investigations did not find any pre-explosion outburst in the years before the discovery [11, 14, 28, 45, 51, 59], but a periodical behavior with a periodicity of about 1000 days [28, 59].

4. High Energy Observations

SN 2023ixf was observed with NuSTAR at 4, 11, 21, 30, 58 days [17, 44], with Chandra at 13, 86 days [8, 44] and with XMM-Newton at 9, 30, 58 days after the explosion [44]. Early NuSTAR spectra showed a hot thermal bremsstrahlung continuum and the presence of Fe Kα line, supporting the presence of a dense and confined CSM [17]. The Chandra spectra were dominated by high temperature plasma from the forward shocked region as a result of CSM interaction and suggested the presence of circumstellar matter [8]; the Fe Kα line was detected only at the first epoch [8]. The hard X-ray [17] and soft X-ray [8, 47] observations suggest a high and decreasing neutral hydrogen column density in the region of SN 2023ixf with a constant mass loss rate in the interval 10 to 1.5 years before explosion [8]. The combined X-ray and radio observations from 4 to 165 days after explosion support the presence of a CSM with asymmetries and clumps, with a large mass loss phase of the progenitor in the two centuries before core collapse [44].

SN 2023ixf was not detected by Fermi-LAT in gamma-rays [35], with an upper limit on the gamma ray flux (above 100 MeV) of 2.6×10^{-11} erg cm^{-2} s^{-1} [53]. The non detection of gamma rays has been used to constrain different processes. The expected gamma-ray and neutrino emission in the supernova explosion has a peak around 9 days after the explosion [30]; the comparison with the Fermi observations constrained the cosmic ray production efficiency to be below 10% [30]. The non detection of gamma rays has been used to constrain the energy transferred to the population of hadronic cosmic rays during the very early expansion stage [36], with a maximum efficiency of the cosmic ray acceleration of 1%, inconsistent with the 10% value of supernovae. The gamma ray non detection has alos been used to constrain MeV scale Axion Like Particles (ALPs) [41].

5. Neutrino Observations

Supernovae are among the sources that are possible emitters of high energy neutrinos, contributing to the IceCube diffuse flux [16]. The early neutrino observations of SN 2023ixf with Super-Kamiokande and IceCube were both negative [3, 43, 61], with an upper limit on muon neutrino flux of 7.3×10^{-2} GeV cm^{-2} [61]. However, the IceCube detection threshold for the bolometric luminosity in the MeV region is quite large [3]. The expected neutrino flux in SN 2023ixf is below the current IceCube sensitivity [9]. The interaction of the supernova ejecta with the dense CSM could lead to PeV protons via shock acceleration, that can produce high energy gamma-rays and neutrinos via inelastic pp collisions [53]; upper limits on gamma-ray flux and on neutrino flux from SN 2023ixf via the pp interaction channel has been set [53]. The estimated rate of low energy neutrinos at the distance of SN 2023ixf is about one event in Hyper-Kamiokande [18], considering the possibility that jets can power supernova ejecta producing high energy neutrinos during the interaction with the strong radiation field in the explosion. So far, no significant spatial or temporal correlation of neutrinos with known supernovae has been found [2].

6. Gravitational Observations

After the conference, the LIGO-Virgo Collaboration has published a paper about the gravitational observation of SN 2023ixf [1]. The search window during gravitational radiation could have been emitted was five days. No gravitational waves were detected when at least two interferometers out of the three interferometers in the network were observing, about 14% of the five day window. Constraints on the gravitational emission mechanism of core collapse supernovae in the range from 50 Hz to 2 kHz, improving the constraints obtained in the previous runs by one order of magnitude, with the constraint on the ellipticity of the proto-neutron star as low as 1.08 at frequencies above 1200 Hz [1].

7. Conclusions

SN 2023ixf is a close type II supernova that has been the target of multimessenger investigations, producing an understanding of the progenitor and the physical mechanisms governing the evolution and constraining a number of models, also at hgih energies.

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