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## ► To cite this version:

Cristina Andrade, Pierre-Alexandre Duverne, Jialian Liu, Felipe Navarete, Abdelaziz E Abdelaziz, et al.. GRANDMA observations of SN 2023wrk, a luminous type Ia supernova with significant unburned carbon in the outer ejecta. *Research Notes of the AAS*, 2024, 8 (10), pp.273. 10.3847/2515-5172/ad8bbb. hal-04815956

**HAL Id: hal-04815956**

**<https://hal.science/hal-04815956v1>**

Submitted on 13 Jan 2025

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DRAFT VERSION NOVEMBER 25, 2024

Typeset using L<sup>A</sup>T<sub>E</sub>X default style in AASTeX631

## GRANDMA Observations of SN 2023wrk, a Luminous Type Ia Supernova with Significant Unburned Carbon in the Outer Ejecta

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## ABSTRACT

First detected on 2023-11-04 by the Gravitational-wave Optical Transient Observer (GOTO), SN 2023wrk is a Type Ia Supernova (SNe Ia) at 40 Mpc, with significant unburned carbon in the outer ejecta. In this note, we present photometric and spectroscopic observations and analysis conducted by the Global Rapid Advanced Network Devoted to the Multi-messenger Addict (GRANDMA) over a 115-day period, which includes 78 days of measurements. The observations were contributed by both amateur and professional astronomers. Liu et al. (2024) analyzed the physical processes involved, and compared the evolution of color and spectral lines. We conclude that SN 2023wrk is the second 1999aa-like object with strong carbon absorption lines that has ever been found, which enriches our understanding of the subclass of 1999aa-like SNe.

## 1. GRANDMA

The Global Rapid Advanced Network Devoted to the Multi-messenger Addict (GRANDMA) collaboration is a network of ground-based facilities dedicated to time-domain astronomy, focused on electromagnetic follow-up of gravitational-wave progenitors and other transients. The network contains 36 telescopes from 30 observatories, 42 institutions, and groups from 20 countries. GRANDMA utilizes wide and narrow field-of-view telescopes distributed across five continents (Antier et al. 2020a,b; Aivazyan et al. 2022; Kann et al. 2023).

GRANDMA’s network extends to its citizen science project titled Kilonova-Catcher (KNC)<sup>1</sup> that allows amateur astronomers to contribute to the GRANDMA campaigns. GRANDMA uses a dedicated web application `SkyPortal` (van der Walt et al. 2019; Coughlin et al. 2023), integrated into GRANDMA’s communication system, which sends out alerts to the network with the coordinates of potential candidates and allows for real-time coordination and analysis by the collaboration.

## 2. OBSERVATIONS

GRANDMA observed SN 2023wrk on 2023-11-06 with the TRT-SRO instrument in Thailand at 2023-11-06 11:56:16, approximately 28 hours after the GOTO detection on 2023-11-04 05:29:46. Observations concluded on 2024-02-26 19:49:19 UTC with the TNT telescope, 115 days after the first observation. The full dataset comprises more than 300 images obtained from 10 professional telescopes, along with more than additional 300 data points collected from 17 amateur telescopes. These observations span multiple bands, including Johnson Cousins  $B, V, R, I$  and Sloan filters in  $g, r, i, z$ .

In this note, we present GRANDMA contribution related to SN 2023wrk. These observations build upon the results presented in Liu et al. (2024), Early-Time Observations of SN 2023wrk: A Luminous Type Ia Supernova with Significant Unburned Carbon in the Outer Ejecta (hereafter referred to as L24).

## 3. ANALYSIS

The images underwent telescope-specific pre-processing, including: bias, dark subtraction, and flat-fielding. For some images, image co-addition was performed using the `Swarp` software (Bertin 2010) to enhance signal-to-noise ratio and astrometric solutions were acquired using `Astrometry.net` (Lang et al. 2010).

The photometric analysis was conducted using `STDPipe`<sup>2</sup> (Karpov 2021), a python package using pre-configured scripts for image analysis. In particular, we used the online implementation of the package called `STDweb`, available at <http://stdweb.favor2.info/>.

The analysis process starts by masking saturated pixels, image edges and cosmic rays removal using the `AstroSCRAPPY` (McCully & Tewes 2019) code implementing the original `LACosmic` (Dokkum (van) 2001) algorithm. Then, we performed the photometry using circular apertures with the radius equal to the average FWHM of stars in each image. FWHM, in turn, was estimated using the median of values measured for every star by `SExtractor` (Bertin & Arnouts 1996), with saturated stars and those with  $S/N < 20$  excluded. The background for every star was estimated locally using a circular annulus with the inner and outer radii of 5 and  $7 \times \text{FWHM}$ .

For photometric calibration, we selected the catalogues based on the filter used for the images – for the ones acquired in Sloan-like filters the Pan-STARRS DR1 (Chambers et al. 2016), while for the ones in Johnson-Cousins we used the Gaia DR3 Syntphot (Gaia Collaboration et al. 2023) catalogue that provides synthetic photometry from low-resolution (XP) spectra of stars observed by Gaia.

In addition, the images taken without a filter of KNC-Unistellar span a wide band from near UV to near IR, posing challenges for standard calibration. We addressed these images by using the  $G$  band of the Gaia eDR3 catalogue (Gaia Collaboration et al. 2023) as it covers a similar range to Unistellar instruments. It resulted in a color term correction  $\leq 0.1$ , rendering it negligible.

The data reduction for OHP spectra employed the `MISTRAL` tool<sup>3</sup>, a Python-based reduction package. Spectral data from OHP and TNG were delivered in absolute fluxes, while KNC provided relative fluxes. Absolute calibration of KNC spectra involved utilizing standard stars and SDSS- $r$  or Bessel- $V$  magnitudes for correction. OHP’s wavelength calibration relied on Hg, Ar, and Xe lamps, with flux calibration referencing the Hiltner 600 spectro-photometric standard.

## 4. RESULTS

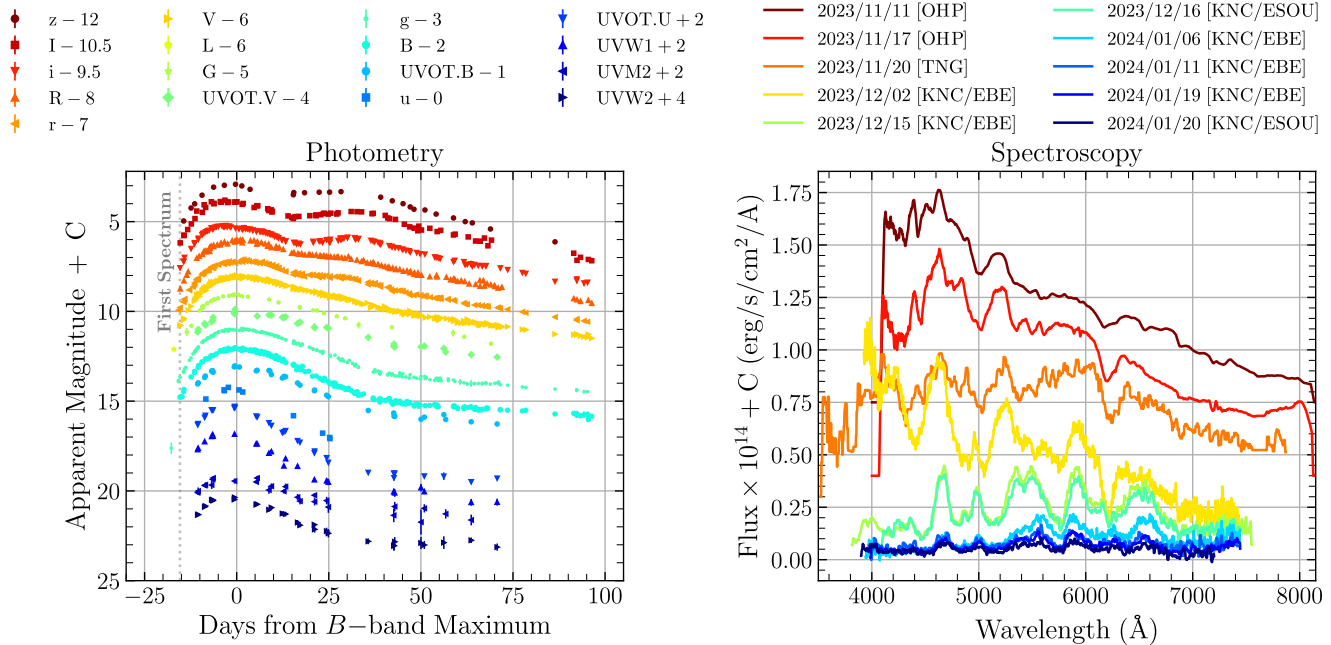
The left panel in Figure 1 shows the photometric lightcurves acquired by GRANDMA and KNC<sup>4</sup>. A summary of our photometric observations is presented in Table 2 of L24 (Liu et al. 2024), including telescope names, their filters and number of images. The complete photometric data of SN 2023wrk is listed in Table 3 of the same paper.

<sup>1</sup> <http://kilonovacatcher.in2p3.fr/>

<sup>2</sup> <https://gitlab.in2p3.fr/icare/stdpipe>

<sup>3</sup> <https://github.com/cylammarco/ASPIRED>

<sup>4</sup> without YFOSC contribution presented in Liu et al. (2024)



**Figure 1.** The left panel shows the UV/Optical photometric lightcurves obtained by GRANDMA and kilonova-Catcher. The plots also includes the Swift observations of SN 2023wrk. The right panel corresponds to the various spectra obtained by GRANDMA OHP and TNG facilities along with the KNC observations.

The right panel of Figure 1 illustrates the optical spectral evolution of SN2023wrk from Nov 11th, 2023 to Jan 20th, 2024. Each curve corresponds to the spectrum of the source taken at different epochs.

A redshift of  $z=-0.02351$  was estimated from the SiII  $\lambda 6355\text{\AA}$  absorption feature on its rest wavelength frame on 2023-12-02 (MJD=2460280.556). The identified absorption features in the rest frame, include SiII $\lambda 4128\text{\AA}$ , MgII $\lambda 4481\text{\AA}$ , SiII $\lambda 5041\text{\AA}$ , FeII $\lambda 5169\text{\AA}$ , NaD $\lambda 5850\text{\AA}$ , SiII $\lambda 5654\text{\AA}$ , HeI $\lambda 5876\text{\AA}$ , and SiII $\lambda 6355\text{\AA}$ . The central wavelength ( $\lambda_{central}$ ) was used to estimate the redshift of the line. The radial velocity of the ejecta ( $v_{rad,ejecta}$ ) was estimated by considering the radial velocity of the host galaxy IC 694 (-3280 km/s, Aalto et al. 1997).

Details of each spectroscopic observation are summarized in Table 5 of L24 (Liu et al. 2024), highlighting: date, phase relative to the B-band maximum, range, exposure(s), and instrument/telescope.

Our main results are:

(i) The strong carbon absorption at first may be related to a collision of the ejecta and nearby, unbound carbon. Then, this carbon feature disappears quickly in subsequent evolution but it reappears at around the time of peak brightness. The reappearance of the carbon feature indicates that the carbon is located deeper in the ejecta, becoming visible at a later phase as the supernova expands and increases in transparency. This allows us to see deeper regions that were initially obscured.

(ii) The constant  $B - V$  color at early times can be explained by outward-mixing  $^{56}\text{Ni}$  ((see 2016ApJ...826...96P)) predicted by the simulation of 3d delayed-detonation (see 2005ApJ...623..337G).

(iii) The diversity of carbon features at very early times among SNe Ia with evident carbon lines may be due to variations in the mass and density of unbound carbon in different supernovae which show prominent carbon features.

All these observational properties of SN 2023wrk are consistent with pulsational delayed-detonation or carbon-rich CSM interaction models.

Acknowledgments for this work are available in the [online repository](#) of the GRANDMA collaboration.

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