9th IAA Planetary Defense Conference – PDC 2025
5-9 May 2025, Stellenbosch, Cape Town, South Africa

IAA-PDC-25-0X-XX

PRE-IMPACT DETECTION OF CHELYABINSK-TYPE OBJECTS IN THE THERMAL INFRARED

Thomas Müller(1), Luca Conversi(2), Javier Licandro(3), Marco Delbo(4), Alan Fitzsimmons(5), Karri Muinonen(6), Marcel Popescu(7), Paolo Tanga(4), Richard Moissl(2)

(1) Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse, 85748 Garching, Germany; tmueller@mpe.mpg.de
(2) European Space Agency – ESRIN, Via Galileo Galilei, 00044 Frascati (RM), Italy
(3) Instituto de Astrofísica de Canarias, C/ Vía Láctea, 38205 La Laguna, España
(4) Observatoire de la Côte d'Azur, Bv de l'Observatoire, 06304 Nice, France
(5) Astrophysics Research Centre, Queen's University Belfast, UK
(6) Department of Physics, P.O. Box 64, 00014 University of Helsinki, Finland
(7) Astronomical Institute of the Romanian Academy, 5 Cuţitul de Argint, 040557 Bucharest, Romania

Keywords: *Space mission, NEO, survey, imminent impactors, risk list, astrometry*

Abstract

We investigate the feasibility of detecting decameter-scale objects on day-side trajectories in infrared wavelengths from space, prior to their close encounters with Earth. Specifically, we examine a 20-m object on a Chelyabinsk-progenitor orbit (Jan/Feb 2013) and the 60-m potentially hazardous asteroid 2024 YR4 (Nov/Dec 2024 & 2032) during their respective approaches to the Earth-Moon system. Considering the solar elongation constraints of the NEO Surveyor and NEOMIR missions (both located at L1), along with a detection threshold of 100 μJy at 8 μm, we find that both missions would be capable of detecting the objects - hours in advance with NEO Surveyor and several days ahead with NEOMIR. We also address limiting factors such as the elevated infrared sky background due to zodiacal dust emission and the high apparent motion of targets near Earth. Finally, we discuss the challenges associated with observing asteroids at low solar elongation and large phase angles, where we lack good-quality IR validation data.

Introduction

The Chelyabinsk meteor entered Earth's atmosphere on 15 February 2013, producing a shock wave that injured about 1,500 people and damaged thousands of buildings. Despite its relatively large size (~20 m), the progenitor asteroid approached Earth undetected. Its radiant was too close to the Sun for standard near-Earth asteroid (NEA) search programmes. In addition, it was very faint due to the high phase angle illumination geometry, and very fast moving. Also, the three times larger NEA 2024 YR4, which will have an extremely close Earth-Moon encounter in Dec. 2032, was only discovered two days after it's close Earth passage on Dec. 25, 2024.

We examine the potential for early detection of a 20-m object on the trajectory of the Chelyabinsk progenitor [Popova2013], and of the potentially hazardous 60-m asteroid 2024 YR4 [Rivkin2025] using upcoming infrared (IR) space initiatives, such as NASA's NEO Surveyor project [Mainzer2023, Masiero2024a, Masiero2024b] and ESA's planned NEOMIR mission [Conversi2024, Conversi2025]. Both missions have a baseline telescope size of 0.5 m and will operate from the Lagrangian point L1 (at about 1.5 million or 0.01 au distance from Earth in the direction of the Sun) in the mid IR regime at wavelengths between 4 and 10 μm. IR observations from space offer key advantages: (i) enhanced Sun-asteroid contrast (compared to visible wavelengths), (ii) small, fast-rotating object are (nearly) isothermal which make IR detections at high phase angles easier, (iii) immediate good-quality size estimation upon IR detection, and (iv) feasibility of observations near the Sun.

Observational constraints

Objects like the Chelyabinsk progenitor (ChPG) or 2024 YR4 (YR4) can only be detected while being inside the planned sky accessibility window. Figure 1 shows the **solar elongation** of both targets, as seen from L1 during the 30 days before Earth encounter. NEO Surveyor will scan the sky at solar elongations between 45° and 125° and ecliptic latitudes between -41.9° and +41.9° (indicated in red), while NEOMIR is covering a ring around the Sun between 30° and 70° solar elongation (marked in blue).

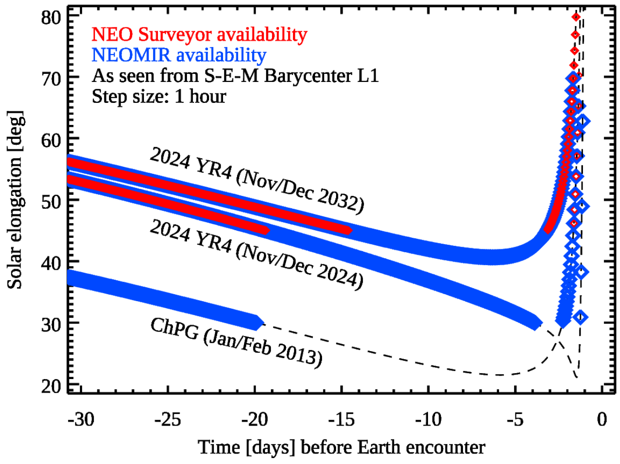


Figure 1: *The L1-centric solar elongations of the ChPG (in Jan/Feb 2013) and YR4 (in Nov/Dec 2024 and 2032) during 30 days before Earth encounter. The long blue paths indicate excellent observing conditions for both targets by NEOMIR. The short and less favourable NEO Surveyor availability is shown in red.*

Both targets are accessible (from L1) before their close Earth encounter, but NEOMIR's observing strategy offers the possibility to catch the targets much earlier and for longer periods of time.

Observing in the IR close to the Sun suffer from **high sky background** dominated by the thermal emission of zodiacal dust. Figure 2 shows the total sky background (zodiacal light emission, diffuse interstellar medium, stellar confusion, extragalactic background) [IPAC Background Model] along the apparent sky trajectory of the ChPG during the last 14 days before encounter, and for different wavelengths. The extremely high mid-IR sky background at small solar elongations makes the detection of faint objects more difficult.

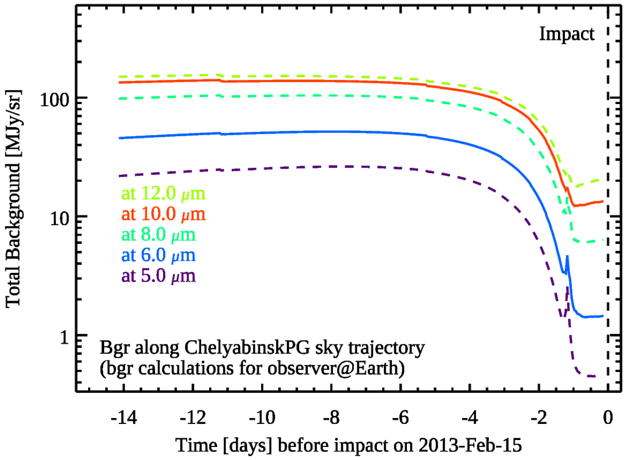


Figure 2: *The calculated sky background along the ChPG trajectory during the last 14 days before impact is shown for different wavelengths: 10 μm (red solid line), 6 μm (blue solid line), and 5, 8, and 12 μm (dashed lines). The background is dominated by zodiacal light emission.*

A small bump in the background appears approximately one day before impact. This increase is due to enhanced interstellar medium (ISM) emission and confusion noise from stars in the dense regions of the galactic plane.

The mid-IR background brightness increases also with wavelength, driven by the zodiacal light which has a blackbody-like spectral shape with temperatures between about 260 and 300 K [Abraham1999].

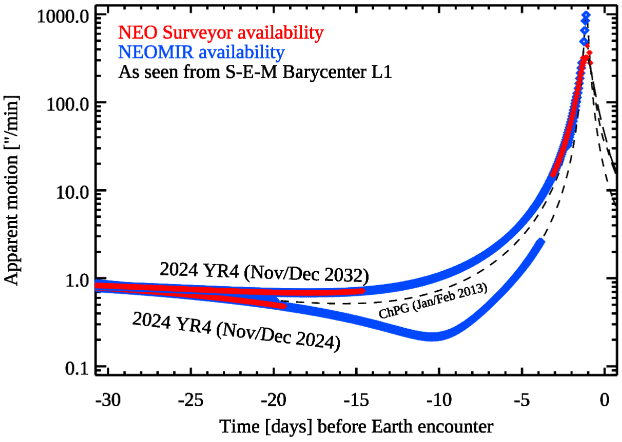


Figure 3: *The apparent motion during the last 30 days before Earth encounter (and as seen from L1).*

The **high apparent motion** of objects in the close vicinity to Earth can also be a limiting factor for good-quality detections. Our two targets have moderate apparent motions below 10 arcsec/min up to about three days before impact or Earth encounter (as seen from L1), see Figure 3. Then, the apparent motion increases dramatically and reaches values above 1000 arcsec/min during close-L1 proximity. Short integration times (e.g., 1-10 sec) are therefore needed to avoid streaking effects and to allow for acceptable astrometric solutions in the mid-IR images.

IR brightness of asteroids

In literature, there exists a range of widely used and validated thermal models to predict the IR fluxes of small atmosphereless solar system objects (e.g., [Delbo2015], [Müller2025], and references therein). These models calculate the surface temperature distribution based on the object's distance from the Sun, albedo, spin state, and thermal properties. The resulting temperature distribution, when combined with surface emissivity characteristics, determines the amount of IR radiation emitted at specific wavelengths, as observed under a given phase angle. However, due to the lack of good-quality measurements, the models (for disk-integrated flux calculations) are only tested up to phase angles of about 90° (half-Moon situation). Observations at larger phase angles are difficult to obtain from Earth or space as telescope pointings are restricted to solar elongations typically larger than 60°. NEO Surveyor and NEOMIR want to detect objects coming out of the Sun's glare and plan telescope pointings closer to the Sun (see Figure 1). But then, the asteroids are seen under large phase angles, comparable with a "sickle" Moon (see Figure 4).

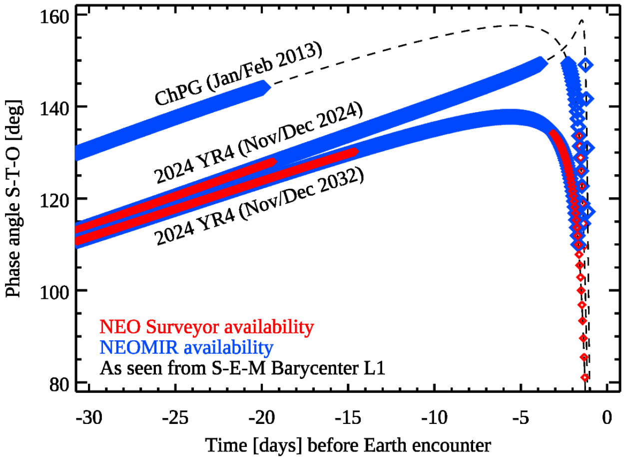
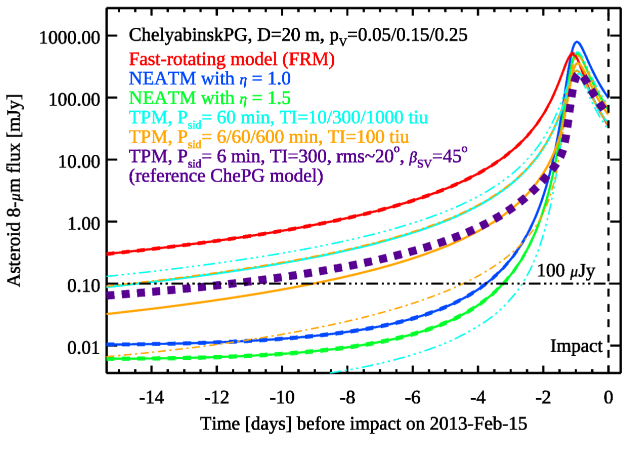


Figure 4: *The phase angles of all 3 cases during the last 30 days before Earth encounter, together with their visibility periods.*

During the last month before Earth encounter, the ChPG and YR4 (in 2024 and 2032) are seen under phase angles in the range between about 100° and up to about 150°. In Figure 5 we show model predictions for the ChPG based on the near-Earth asteroid thermal model (NEATM [Harris1998]), the fast-rotating model (FRM [Lebofsky1978]) and a thermophysical model (TPM [Lagerros1998]). At high phase angles, the predictions deviate considerably, however, the focus on small, fast-rotating NEAs will constrain the meaningful parameter space again (see purple dashed line in Figure 3, top, which indicates our baseline ChPG reference model).



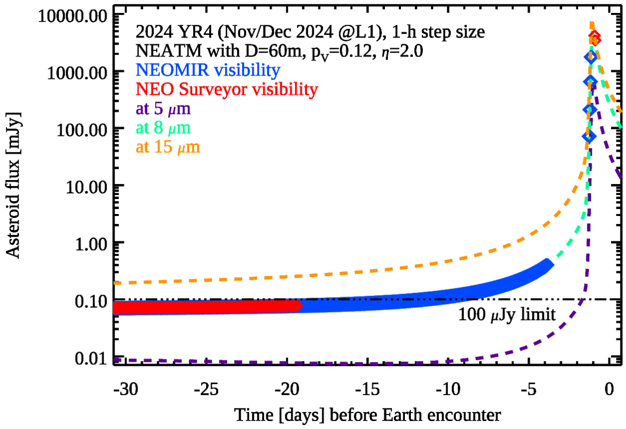


Figure 5: *Thermal model predictions for the ChPG (top) and YR4 (bottom) during the days before Earth encounter where both targets are seen under very large phase angle (>>100°). For the ChPG we show the range of 8 μm fluxes for different model and model parameters. For YR4 we present NEATM fluxes at 5, 8, and 15 μm. The 100 μJy limit is close to the quantified sensitivity of NEO Surveyor [Mainzer2023].*

The true detection limits for a given observation are influenced by many aspects, including the exposure times, sky background levels, filter and detector properties, or straylight levels. We assumed a threshold of about 100 μJy where a detection of a point source (about 5 times above the noise level) seems to be feasible.

In principle, the ChPG exceeds this detection threshold already about 10 days before impact (see Figure 3 top), while in the visible it would still be fainter than magnitude 30. But due to the solar elongation constraints, NEOMIR would be able to detect it 2.2 days and NEO Surveyor 1.6 days before impact. The theoretically possible 10-day lead time would only be doable if observations down to solar elongation of about 21° would be allowed.

The YR4 is more favorable, at least for NEOMIR. In December 2024, it would have been well within the visibility zone and passing the detection threshold more than 10 days before its close encounter with Earth on December 25, 2024. It is worth to note that YR4 was in the visible range at that time fainter than magnitude 25 and well beyond detection capabilities of current ground-based surveys. NEO Surveyor would have been able to detect YR4 only about 1 day before the Earth encounter in 2024 due to the 45° elongation limit. In 2032, YR4 will be in the NEOMIR visibility region and above the 100 μJy threshold during more than two weeks before the Earth/Moon encounter on December 22, 2032, while for NEO Surveyor, again due to the 45° elongation limit, observations are only possible for 2 days (Dec 19-21, 2032).

Conclusion

Placing a small, 0.5 m IR survey telescope in L1 has clear advantages over ground-based large visible survey telescopes. Mid-IR detections of decameter-scale objects are possible days to weeks before a close Earth encounter or impact, even if they come out of a close-to-Sun proximity zone. Table 1 summarizes the different pre-encounter constraints and time scales for the two targets considered here.

Table 1: *Detection lead time before Earth encounter for NEO Surveyor, NEOMIR, and when relaxing the solar elongation constraint to 20°. We considered object sizes of 20 m (ChPG) and 60 m (2024 YR4), default thermal model assumptions and a detection threshold of 100 μJy at 8-μm.*

Target	NEO Surveyor; 8-μm flux > 100 μJy	NEOMIR; 8-μm flux > 100 μJy	SOT > 20°; 8-μm flux > 100 μJy
ChPG	14 hours	~1 day	~10 days
YR4 (2024)	2 hours	~10 days (2.5-day gap)	~10 days
YR4 (2032)	50 hours	~18 days	~20 days

In the context of the ChPG, YR4 (in 2024 and 2032), and other decameter-scale objects on similar trajectories, limitations are related to the solar elongation limits of the telescopes, the high (zodiacal) background close to the Sun, wavelength and width of instrument band(s), exposure times and observing strategy. At longer wavelength, closer to 10 μm or beyond, the target-to-background flux ratios are getting better, but limitations due to the detector's response function, possible straylight and thermal self-emission contributions kick in. Short exposure times (1-10 sec) would avoid streaking effects during phases where the objects have high apparent motions and would enable better quality astrometry. At the same time, short multiple exposures within a given telescope pointing, would allow for synthetic tracking techniques, similar to what has been done for JWST-MIRI observations to detect decameter-size asteroids [Burdanov2025].

A high uncertainty in estimating the lead times for the detections is related to modeling the thermal emission of asteroids seen under extreme phase angles larger than 100° (like a "sickle moon"). Thermophysical model predictions using "default" object properties for spin and thermal characteristics might be the solution. However, suitable IR validation measurements on well-known objects seen under a very wide range of phase angles are difficult to obtain via currently available IR facilities [Delbo2025], thermal IR measurements of asteroids at phase angles > 120° are not existing.

References

[Popova2013] Popova, O.P., Jenniskens, P., Emel'yanenko, V., et al., "Chelyabinsk Airburst, Damage Assessment, Meteorite Recovery, and Characterization", Science, 342, 1069-1073 (2013)

[Rivkin2025] Rivkin, A., Müller, T.G., MacLennan, E., Holler, B., Burdanov, A., et al., „JWST Observations of Potentially Hazardous Asteroid 2024 YR4", Research Notes of the AAS, 9, id.70 (2025)

[Mainzer2023] Mainzer, A.K., Masiero, J. R., Abell, P.A., et al., "The Near-Earth Object Surveyor Mission", Planetary Science Journal, 4, 224 (2023)

[Masiero2024a] Masiero, J. R., Kwon, Yuna G., Dahlen, D.W., et al., "The Sensitivity of NEO Surveyor to Low-perihelion Asteroids", Planetary Science Journal, 5 , 113 (2024)

[Masiero2024b] Masiero, J. R., Linder, T., Mainzer, A., et al., "Visual-band Brightnesses of Near-Earth Objects that will be Discovered in the Infrared by NEO Surveyor", Planetary Science Journal, 5 , 222 (2024)

[Conversi2024] Conversi, L., Licandro, J., Delbo, M., Fitzsimmons, A., Muinonen, K., Müller, T., Popescu, M., Tanga, P., Moissl, R., "NEOMIR: ESA's space-based infrared mission for NEO detection and early warning", Proceedings of the SPIE, 13092, 130922H, 8 pp. (2024)

[Conversi2025] Conversi, L., Licandro, J., Delbo, M., Fitzsimmons, A., Muinonen, K., Müller, T., Popescu, M., Tanga, P., Revellino, M. M., Micheli, M., Moissl, R., "NEOMIR: ESA's space-based infrared mission for NEO detection and early warning", in Progress in Planetary Defense, Advances in Astronomy, Special Issue, Lead Guest Editor: Michael Kueppers (2025)

[IPAC Background Model]: https://irsa.ipac.caltech.edu/applications/BackgroundModel/ (and references listed there)

[Abraham1999] Abraham, P., Leinert, C., Acosta-Pulido, J. A., Schmidtobreick, L., Lemke, D., "Zodiacal light observations with ISOPHOT", The Universe as seen by ISO, Eds. P. Cox & M. F. Kessler, ESA-SP 427, 145 (1999)

[Delbo2015] Delbo, M., Mueller, M., Emery, J. P., Rozitis, B., Capria, M. T., "Asteroid Thermophysical Modeling", in Asteroids IV, Patrick Michel, Francesca E. DeMeo, and William F. Bottke (eds.), University of Arizona Press, Tucson, 895 pp. ISBN: 978-0-816-53213-1, 2015., p.107-128 (2015)

[Müller2025] Müller, T. G., Conversi, L., Licandro, J., Delbo, M., Fitzsimmons, A., et al., „Pre-Impact Detection of Chelyabinsk-type Objects in the Thermal Infrared: Possibilities and Limitations", Advances in Astronomy, Progress in Planetary Defense, Special Issue, submitted (2025)

[Harris1998] Harris, A. W., "A Thermal Model for Near-Earth Asteroids", Icarus, 131, 291-301 (1998)

[Lebofsky1978] Lebofsky, L. A., Veeder, G. J., Lebofsky, M. J., Matson, D. L., “Visual and Radiometric Photometry of 1580 Betulia”, Icarus, 35, 336-343 (1978)
[Lagerros1998], Lagerros, J.S.V., „Thermal Physics of Asteroids”, Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 341. 45 pp. Uppsala. ISBN 91-554-4144-0 (1998)
[Burdanov2025] Burdanov, A.Y., de Wit, J., Brož, M., Müller, T.G., Hoffmann, T., et al.,”JWST sightings of decametre main-belt asteroids and view on meteorite sources”, Nature, 638, 8049, 74-78 (2025)
[Delbo2025] Delbo, M., Beniyama, J., Müller, T.G, Conversi, L., et al., “On the detection and characterization of potential Earth-impacting asteroids from space in the thermal infrared – The large phase angle case”, Advances in Astronomy, Progress in Planetary Defense, Special Issue, submitted (2025)