ASTRONOMY EDUCATION JOURNAL

Astronomy Education Journal, 2026, Vol. 06, No. 1

doi: 10.32374/2026.6.1.152bp
ISSN: 2004-2981 · Published in Sweden

BEST PRACTICE

MOMSTER: a mobile radio meteor detection kit for STEM learning linked to citizen science

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Abstract

Despite growing recognition of the value of integrated STEM approaches in education, truly hands-on, inquiry-driven experiences remain rare in secondary schools. Meteor science offers a compelling opportunity to bridge disciplines such as physics, geography, engineering and mathematics through real-world investigation. This paper describes the development and classroom integration of MOMSTER, a mobile meteor detection kit designed to bring real scientific practice to secondary education. The kit enables students to detect and analyse actual meteor events using radio techniques, fostering inquiry-based learning through direct engagement with live data.

Although the data collected with MOMSTER kits are not research-grade, the project is structurally linked to the Radio Meteor Zoo (RMZ), where students can optionally classify calibrated meteor detections as part of an ongoing citizen science initiative. This modular setup connects education with research: MOMSTER serves as a hands-on entry point, while RMZ provides a channel for contributing to ongoing science.

Early classroom use in Belgian secondary schools showed that giving students tools to detect meteors and direct access to live observations sparked enthusiasm and deeper engagement with science. Teacher autonomy proved critical to success: technical adaptations, including pre-configured laptops and simplified data handling, made the system accessible without specialist knowledge. Modular educational resources enabled flexible integration across STEM subjects, reaching a wide range of learners, and addressing common misconceptions about meteors and radio detection. As a bonus, the introduction of the methodology of radio meteor observations substantially broadened the range of STEM subjects tackled in the accompanying educational resources, reducing an often observed under-representation of mathematics in integrated STEM projects.

This work contributes to educational research on the integration of real-world science into formal learning environments. It shows how inquiry-based projects, when structurally linked to citizen science platforms, can support authentic engagement, curricular relevance, and public participation in science. Its novelty lies in combining real-time radio meteor observations with modular classroom materials and a structural link to a citizen science platform, providing a hybrid model rarely available in secondary STEM education.

Keywords: Meteor science; STEM education; Citizen science; Astronomy education; Public engagement in science

1 Introduction

Education in Belgium continues to shift from discrete school subjects (such as physics and geography) toward integrated STEM approaches (science, technology, engineering and mathematics; see Section 7.1 for the list of abbreviations), and, in parallel with international trends, requires more experiential, curiosity-driven learning tools (e.g., Portillo-Blanco et al., 2024). Already in 2015, an authoritative position paper by the Royal Flemish Academy of Belgium for Science and the Arts highlighted the urgent need for more inquiry-based STEM education to strengthen scientific literacy and student engagement in STEM subjects (Veretennicoff et al., 2015). Even though secondary education is organised separately in the Dutch and in the French-speaking community in Belgium, with distinct curricula, the need for cross-disciplinary, inquiry-driven learning is widely recognised across the country. A more recent evaluation report by the ESERO Belgium consortium (Kolenberg et al., 2021) confirmed that STEM initiatives are increasingly promoted, but real hands-on projects that bridge disciplines and involve inquiry-based learning (IBL) remain rare in secondary education.

Such projects can add significant value to the successful implementation of integrated STEM approaches in formal educational settings, as they often comprise (a) integrated/interdisciplinary approaches within a (b) real-world context, often requiring (c) inquiry- and (d) teamwork-based (e) problem solving skills, which are five of the seven principles stated in the review paper on integrated STEM education by Portillo-Blanco et al. (2024). The same authors, however, noted a concern over an imbalance in disciplinary focus often observed in integrated STEM projects, where mathematics is often underrepresented in the approach.

Meteor science offers a unique opportunity to address the need for more integrated STEM projects, as it provides valuable insights into comets and asteroids, solar system evolution, and atmospheric interactions, which are topics well relatable to curriculum goals within the geography, chemistry and physics courses in formal education. Complemented by the use of radio meteor waves as a core method to detect meteors, this topic may offer an entry into an even broader range of STEM domains, such as wave physics, signal interpretation, and mathematical data analysis, making it even more suitable for integrated STEM teaching by addressing the concerns of Portillo-Blanco et al. (2024) about the under-representation of mathematics and engineering in such projects.

Despite their relevance and accessibility, meteors remain largely under-represented in classroom teaching (e.g., Lonc, 1999; Snjegota and Rattenbury, 2017). To bridge this gap, we developed MOMSTER (MObile Meteor STation for Education & outReach): a portable, inquiry-driven kit that brings meteor detection into classrooms. MOMSTER connects academic meteor research and secondary education in a tangible way, building on the scientific BRAMS (Belgian RAdio Meteor Stations) radio meteor detection network in Belgium (see 2.1). The kit includes a small antenna and a receiving system, giving students the tools to detect meteors themselves, along with adaptable lesson materials. Unlike the permanent BRAMS installation, MOMSTER is designed specifically for temporary classroom deployment, prioritising portability and curricular integration over research-grade calibration.

The MOMSTER project pursues three main objectives:

1. **Promote STEM learning:** Meteor science and live radio observations are used to ignite curiosity and exploration in interdisciplinary subjects. The integration of radio meteor detection into classroom activities aligns naturally with existing curricula and encourages students to explore careers in STEM.
2. **Connect students to citizen science:** While the MOMSTER hardware does not provide research-grade calibrated data, the corresponding classroom materials encourage students and teachers to also engage with the equivalent online citizen science project Radio Meteor Zoo (RMZ, see Section 2.2), where volunteers classify meteor detections that comply with academic quality and calibration standards, ultimately contributing to real academic research, and hence linking inquiry-based school research with genuine citizen science and public research.
3. **Engage the wider public:** Our objective is to expand the impact of the BRAMS network and develop outreach materials and local partnerships. By engaging visitor centres, educators, and local media, MOMSTER increases visibility of the BRAMS project and participation in citizen science.

This paper begins by describing the scientific basis of meteor observation and radio detection, with specific attention to the BRAMS network and the Radio Meteor Zoo (Section 2). Then it discusses the origins of the MOMSTER project and its early adoption in classrooms, including the initial design of the detection kit and the accompanying educational materials (Section 3.1). Subsequent sections present practical lessons from classroom deployments, technical and pedagogical refinements, and strategies for curricular integration and teacher support (Section 3.2). The paper also explores how MOMSTER is linked to the RMZ to bridge education and research participation (Section 3.3). Based on these developments, we present the didactical analysis and lessons learnt from the school implementations (Section 4), and conclude with recommendations and future perspectives (Section 5).

2 Background

Meteoroids are small bodies in the solar system that range from roughly 30 micrometres to 1 metre in diameter (Koschny and Borovicka, 2017). When they enter a planet's atmosphere and ablate due to friction with atmospheric molecules, they emit visible light, a phenomenon known as a *meteor*, or more commonly, a "shooting star". If the object survives its passage through the atmosphere and reaches the ground, the remaining fragment is referred to as a meteorite.

Meteors are typically classified into two categories: *shower meteors* and *sporadic meteors* (Rendtel, 2024). Shower meteors originate from trails of dust and debris released by periodic comets or asteroids as they orbit the Sun. These trails remain in the solar system and are replenished with each return of the parent body. When Earth's orbit intersects one of these trails at a specific period, particles of the trail enter the atmosphere and produce a meteor shower. Because meteoroids in a shower follow nearly parallel trajectories in space, their paths appear to converge toward a single point in the sky, known as the *radiant*. This is a perspective effect, similar to the way train tracks appear to meet on the horizon. The radiant typically gives the shower its name: for example, the radiant of the *Perseids*, active in mid-August, is located in the constellation Perseus.

Sporadic meteors, on the other hand, come from particles that are not associated with any currently active stream. These may be remnants of older dust trails that have been gravitationally perturbed (especially by the gas giants like Jupiter) and are no longer linked to their original parent body. Most of these particles are also bound to the solar system, but in rare cases interstellar particles may enter Earth's atmosphere.

The study of meteors can provide insight into the history of the solar system, the evolution of comets and asteroids, and the distribution of dust in the solar system. Meteors also interact with the molecules and atoms of the upper atmosphere, at altitudes typically between 80 and 120 km, creating permanent layers of metals that play an important role in atmospheric chemistry. Furthermore, meteoroids pose a threat to spacecraft due to their high kinetic energy (Soja et al., 2014).

2.1 Radio detection of meteors: the BRAMS network

Although optical detection is the most direct way to observe meteors, it is limited to night and clear skies, while meteoroids fall into the atmosphere of the Earth continuously during the day and night. In the BRAMS network, we use radio techniques to detect meteors. Meteoroids ionise atmospheric molecules as they ablate, producing a trail of plasma along their path, which can reflect [1] radio waves emitted by ground-based transmitters (Figure 1). The reflected signal received by a distant antenna is known as a *meteor echo* - an indirect but effective way of detecting meteoroid entries.

In the BRAMS configuration, the transmitter and receivers are relatively close to each other, meaning that the direct signal from the transmitter is also received at the stations. In spectrograms, this appears as a continuous horizontal line at the transmitter frequency. Meteor detection occurs when the ionised trail temporarily reflects or scatters the signal, producing additional features above or below this reference line. The meteoroid therefore does not emit radio waves; rather, the plasma trail acts as a transient reflector of the existing signal.

The characteristics of a meteor echo, such as its duration, power, and shape, depend on various physical parameters, including the meteoroid's size, velocity, and angle of entry. These echoes are continuously recorded and are more easily distinguished when the data are displayed as *spectrograms*, which show the power of the signal as a function of time and frequency. Spectrograms allow users to identify different types of echoes, which are generally classified into two categories: *underdense* (short-lived, a fraction of a second, and caused by smaller particles) and *overdense* (lasting at least one second and produced by larger meteoroids) (Wislez, 2006). An example of a spectrogram with key components labelled is shown in Figure 2.

This radio-based detection method offers several advantages:

1. Radio detection can operate continuously, including during the day. This makes the technique particularly suitable for educational use during regular school hours.
2. Radio waves are unaffected by cloud cover, making observations possible even in poor weather, a major benefit in regions like Belgium with frequent overcast conditions.
3. Radio systems can detect smaller meteoroids than optical methods. Since the meteoroid mass distribution follows a power law, smaller particles are much more numerous than larger ones. A single BRAMS receiving station, for example, typically detects around 1500-2000 meteors per day, whereas an optical station in Belgium observes only a few tens.

Today, the BRAMS network consists of approximately 50 receiving stations distributed throughout Belgium and neighbouring regions, operating continuously. The stations are located in scientific and public institutions as well as private grounds. They detect reflections of a continuous, circularly polarised sine wave transmitted at 49.97 MHz by a beacon with an output power of 340 W, located at the Centre de Géophysique du Globe in Dourbes, southern Belgium (50.10°N, 4.58°E).

2.2 Citizen science and the Radio Meteor Zoo

Automatic detection of meteor echoes, particularly overdense ones, is challenging due to their irregular shapes and signatures. The large volume of observational data also made manual annotation by the BRAMS team unfeasible.

To address this, the RMZ was launched in August 2016 (Calders et al., 2016). As an online citizen science project, it invites volunteers to visually classify meteor echoes in BRAMS spectrograms, especially during meteor showers, when both the number of meteors and the proportion of overdense events increase. Since its launch, the platform has engaged more than 20,000 volunteers who have analysed more than 140,000 spectrograms, detecting over a million meteors. Figure 3 shows a screenshot of the RMZ interface used for this classification task. The project is still active.

3 MOMSTER: from concept to classroom

3.1 Origin of the project and early developments

MOMSTER builds on previous efforts to bring scientific research into classrooms, particularly through the Erasmus+ project BRITEC (Bringing Research InTo thE Classroom) (Goździk et al., 2021; Tasiopoulou et al., 2021), which promoted IBL through collaboration between researchers and teachers. KU Leuven coordinated the Belgian component of BRITEC (where radio meteor science was a key theme) and the schools engaged with BRAMS data and the RMZ. However, these activities often re-

1 The underlying physical process is technically a form of coherent scattering by ionised particles along the meteoroid trail, but in practice the effect is typically referred to as "reflection" due to the strong signal received from the specular reflection point. To avoid unnecessary complexity, we use "reflection" throughout this paper.

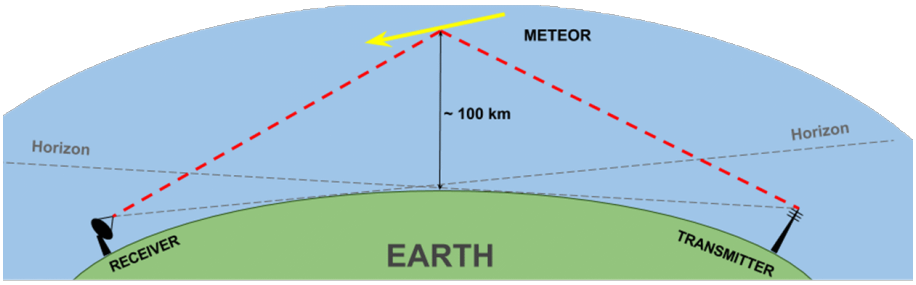

Figure 1. Principle of forward scatter radio meteor detection. A ground-based transmitter's signal is scattered off the ionised trail of a meteoroid entering Earth's atmosphere, allowing distant receivers to detect meteor echoes otherwise blocked by Earth's curvature. A typical reflection height of approximately 100 km is shown. In practice, meteor echoes are usually detected between 80 and 120 km altitude.

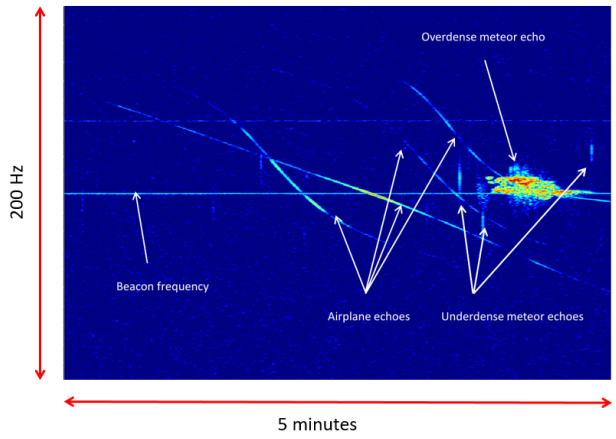

Figure 2. A spectrogram showing several underdense meteors, one overdense echo, the continuous beacon signal (horizontal line), and some aircraft reflections. The horizontal axis covers 5 minutes of data. The vertical axis spans a 200 Hz frequency window centred on the BRAMS beacon frequency (49.97 MHz). Signal power is colour-coded in arbitrary units: blue means a weak (background) signal and red a very strong one.

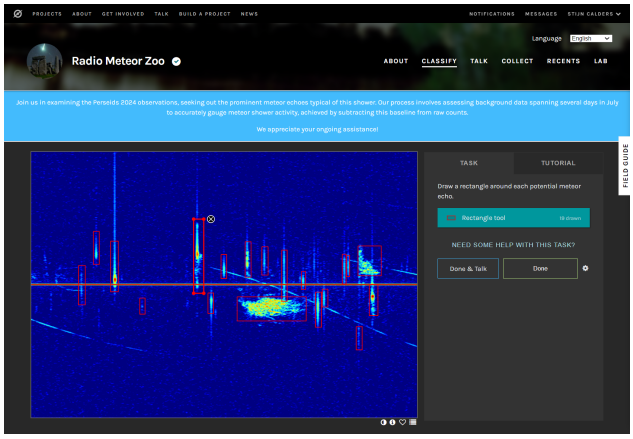

Figure 3. Screenshot of the Radio Meteor Zoo interface, showing a BRAMS spectrogram with user-drawn rectangles around potential meteor echoes. Volunteers assist in classifying these echoes to support scientific analysis of meteor activity.

mained abstract to the students. To create a more hands-on experience, BIRA-IASB initiated the MOMSTER project in collaboration with KU Leuven and the Brussels Planetarium.

Supported by the Europlanet Public Engagement Funding Scheme (2020 call), MOMSTER developed a mobile radio meteor detection kit for classroom use, accompanied by modular teaching materials. This combination enables students to make observations in real time using actual data, while teachers can tailor lessons from a flexible "educational buffet" spanning multiple STEM subjects, supporting deeper and interdisciplinary engagement. A detailed discussion of how these activities operationalise inquiry and interdisciplinary learning is provided in Section 4.

The MOMSTER kit: concept and initial design

Each MOMSTER kit includes a compact antenna, a radio receiver, and a Raspberry Pi computer, pre-configured to record and store observations. The setup is designed to be plug-and-play, enabling quick deployment and easy use in classrooms without requiring advanced technical expertise. The schools use the same type of transmitter and receiver hardware (except for the antenna, see next paragraph) as the operational BRAMS stations. A photo of the receiver unit, housed in a box with a transparent cover, is shown in Figure 4, which provides a view of the internal components - an aspect particularly useful for classes and teachers with a greater focus on technical subjects.

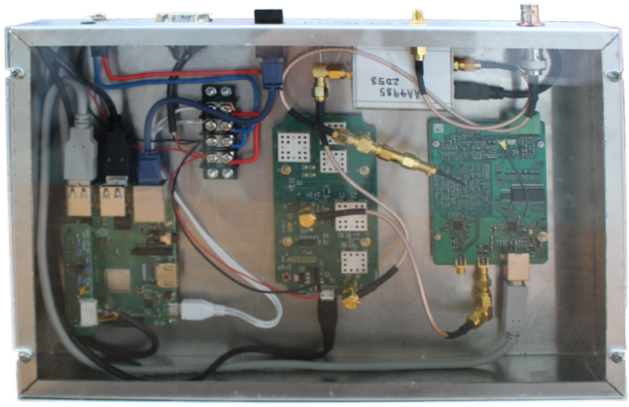

Figure 4. The MOMSTER receiver unit with a transparent cover, showing the internal components such as the radio receiver (at the right) and Raspberry Pi (at the bottom left). Other devices are used for calibration purposes.

MOMSTER uses the same receiver electronics as operational BRAMS stations; yet it is equipped with a smaller, dedicated antenna specifically designed for deployment in educational settings. This compact version allows easier installation in school settings, where space, mounting options, and local interference must be taken into account. The standard BRAMS antenna, on the contrary, is larger and optimised for sensitivity to signals from higher elevation angles, making it better suited for permanent monitoring stations. Although overall sensitivity is comparable between the two, the MOMSTER antenna is more sensitive to signals at low elevation angles, making it more susceptible to local radio frequency interference, its main limitation in noisy environments. Figure 5 shows a side-by-side comparison of the two antenna types, highlighting the trade-off between portability and robustness to local interference in the design of the MOMSTER kit.

Even if the data collected by the MOMSTER kits are not calibrated for use in peer-reviewed scientific research, they are based on actual meteor events and follow the same detection principles as professional BRAMS stations. This gives students access to real, meaningful observations that simulate the research process and foster scientific inquiry in an educational context. Teachers are also shown how to access near-real-time data from the nearest operational BRAMS station to compare their observations and judge if they have set up the MOMSTER kit correctly. Because stations located close to each other should detect largely the same meteor echoes, such comparisons help teachers verify their results and identify potential setup issues.

Tackling misconceptions

Misconceptions about basic astronomical phenomena are well documented in the literature on astronomy education (e.g., Kokrur, 2015; Lelliott and Rollnick, 2010).

Although "shooting stars" are a familiar phenomenon, several misconceptions regularly arise among students and the general public. Based on repeated interactions during workshops and classroom activities, we observed that many students confuse the terms meteor, meteoroid, and meteorite. These terms have different meanings, as explained in Section 2, and understanding them correctly is essential to build accurate mental models. Another common misunderstanding is the idea that meteors are stars falling from the sky, rather than small pieces of space debris. Some students also believe that every visible meteor results in a meteorite landing, while in reality most meteoroids disintegrate entirely in the atmosphere.

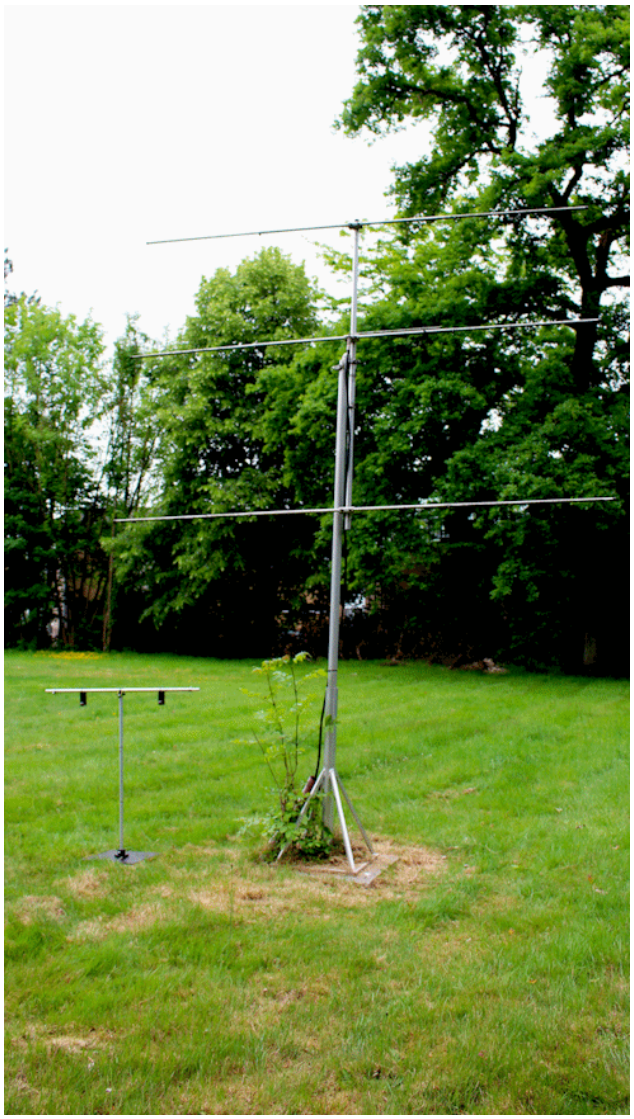

Figure 5. Comparison of the MOMSTER antenna (left) and the standard BRAMS antenna (right). The BRAMS antenna is larger and more sensitive, while the MOMSTER version was designed to be compact, portable, and suitable for school environments.

Radio meteor detection brings its own set of misconceptions. For example, many people initially think that meteors emit radio waves, rather than understanding that the ionised trails reflect existing radio signals. It also often comes as a surprise that meteors can be detected during the day using radio techniques, even though they are invisible to the naked eye.

Even if these specific radio-related misconceptions are not formally documented, they are recurring themes in informal discussions with students and teachers during MOMSTER and earlier BRAMS outreach activities. The MOMSTER educational materials are designed to address these issues directly, using clear explanations, diagrams, and hands-on activities to help students develop a correct conceptual understanding of the meteor detection process.

In addition to clarifying conceptual misunderstandings, introducing radio detection as an observation method offers pedagogical advantages beyond the topic of meteors itself. Because the technique involves wave propagation, signal reflection, and data interpretation through spectrograms, it enables natural links to physics, mathematics, and even geography curricula. In this way, the use of radio observations provides a broader and more versatile entry point into STEM learning than meteor science alone, allowing teachers to address multiple curricular goals through a single thematic context.

The educational buffet: interdisciplinary integration

To support this conceptual understanding and facilitate broader curricular integration, the MOMSTER kit is accompanied by an educational buffet of modular lessons for teachers. This initiative was initially coordinated by KU Leuven and subsequently taken over by International Polar Foundation (IPF). These resources bring the theme of meteors and radio astronomy into the classroom and are freely available in Dutch and French on the MOMSTER website. Teachers can select one or more educational modules depending on their available time and learning objectives:

- **Geography**: the relationship between comets and meteors, which contains also an exercise about the RMZ citizen science project,
- **Physics**: the diurnal variation of the sporadic meteor activity,
- **Mathematics**: calculation of distances using Pythagoras' theorem and geometry used to retrieve the meteoroid's path,
- **Arts**: infographics and science-based art.

These resources are designed for students aged 14 to 18 in order to inspire them to pursue science or technology studies when they enter higher education. In practice, teachers often combine modules (e.g. pairing the geometry of meteor trajectories with the diurnal variation of sporadic meteors) which illustrates how the modular design supports coherent interdisciplinary sequences. A detailed discussion of the interdisciplinary design follows in Section 4.

In 2021, a national art and design competition was organised as an optional enrichment activity to support student engagement with the MOMSTER project. The competition invited secondary school students to explore creative ways of communicating meteor science and radio detection to non-specialist audiences. A total of 33 students (age 14–15) from three Flemish high schools took part, submitting entries in either the 'art' category (n = 29), in which students visually decorated the MOMSTER box, or the 'design' category (n = 4), in which students created an infographic or mini-comic explaining the underlying science. Ten entries were shortlisted and evaluated by an internal jury of 12 members, who selected one winner per category. The winning designs are now included with each MOMSTER kit: one as a sticker on the box (Figure 6), and one as a portable roll-up display. While the competition was a one-off initiative, it served to complement the core STEM-focused activities by supporting creativity and science communication.

Since 2021, MOMSTER kits have been deployed in several secondary schools across Belgium, typically for several weeks at a time. Teachers receive an installation and operation manual and stay in contact with the project team for additional support. This manual includes detailed and illustrated instructions for setting up the antenna (including antenna orientation, recommended placement, and how to assess interference levels), connecting the receiver to the Raspberry Pi, and verifying data collection.

In early deployments, schools had to provide their own Windows laptop, install freeware Spectrum Lab software, and connect it to the Raspberry Pi over a local network. Despite the availability of an extensive and carefully written guide, these steps proved too complex for many teachers and created a significant barrier to independent use.

In addition to school visits, the MOMSTER kit has been used for outreach at a variety of science events. Demonstrations have been organised at Brussels Planetarium, and during open doors at public observatory Urania in Hove, Belgium. The kit was also presented at Fri3d Camp, a biennial technology and maker festival, in August 2022 and 2024 and four times during the astron-

Figure 6. The MOMSTER box, containing the portable antenna, coax cable, and radio receiver, shown here with a student-created design from an optional art and design competition held in 2021. This competition served as an enrichment activity to support student engagement and communication, complementing the core STEM-focused inquiry activities.

omy camp of Oberon, which is the Urania youth section. These activities helped to introduce the topic of radio meteor detection to broader audiences, including families, amateur astronomers, educators, and young science enthusiasts.

3.2 Improved implementation

These early experiences, in schools and at science events, highlighted both the promise and limitations of the initial design, prompting several technical and pedagogical refinements.

The MOMSTER kit: technical challenges and refinements

Following the initial launch, the MOMSTER kit was refined based on teacher feedback and classroom experience. Teachers had difficulty configuring school laptops to interface with the Raspberry Pi and visualising live data. In addition, many expressed the desire to retain their collected data for future use. In response, a major technical upgrade was implemented in early 2022: the integration of a dedicated Linux laptop in the provided material. The laptop is pre-installed with all necessary software and automatically connects to the Raspberry Pi. It features a simplified two-button interface: one button launches Spectrum Lab, which is already configured for use, and the other performs the combined task of transferring data and generating a spectrogram. This modification significantly reduced technical barriers and allowed schools to conduct independent observations more easily.

The lessons learnt from the early technical failures led to improvements in antenna design, preparing spare parts kits, and developing troubleshooting guides for teachers. These adaptations significantly reduced downtime and made the project more resilient. As outlined in Section 3.1, the portable antenna is more sensitive to local interference and installation conditions. These technical characteristics shaped the practical challenges observed during early classroom implementation.

Further pilot testing revealed that the MOMSTER antenna, although portable, was more sensitive to local interference and strongly affected by ground conductivity, especially when installed on surfaces such as flat roofs. To support teachers in choosing suitable installation sites, a live interference indicator with simple feedback messages ("Perfect, sufficient, inadequate") was added, along with targeted setup recommendations that were incorporated into the updated user manual.

Figure 7. Teacher training session organised during the VeLeWe (association of science teachers) congress in Ghent (2022). Teachers received hands-on experience with the MOMSTER meteor detection kits. These sessions were crucial in building teacher confidence, lowering technical barriers, and demonstrating how the kits could be integrated into existing STEM curricula.

The educational buffet: curriculum alignment and teacher support

Further along, MOMSTER partners realised that clearly linking activities to curriculum learning goals significantly increased teacher willingness to adopt the kit. Consequently, each educational module was explicitly aligned with the official regional secondary education objectives.

To build additional teacher confidence, short training sessions (Figure 7) were organised. These provided practical hands-on experience with the equipment and sample lesson applications. The informal feedback collected during these trainings confirmed that the teachers appreciated both the alignment of the curriculum and the added simplicity of the system.

Partnerships and scaling

These pilot tests highlighted the strategic importance of partnering with institutions whose core missions include science education. These organisations offer broader access to public audiences, more in-depth knowledge of educational priorities, and stronger connections with schools, thus enhancing the effectiveness and relevance of MOMSTER's outreach efforts.

Consequently, the MOMSTER team expanded collaborations with science outreach partners: public observatory Urania, Euro Space Centre, and Inforscience platform at the Université Libre de Bruxelles (ULB). These partnerships helped increase the project's visibility and identify new schools interested in the MOMSTER project.

3.3 Linking MOMSTER to citizen science

Despite the fact that MOMSTER was designed to bring real meteor observations into the classroom, the data collected by schools are not calibrated for scientific use (see Section 3.1). In that sense, MOMSTER is best described as an inquiry-based STEM education module, rather than a full citizen science project. However, the project is closely linked to the RMZ citizen science initiative, which allows volunteers to classify meteor echoes based on BRAMS data.

This combination of a classroom-based inquiry module (MOMSTER) with a citizen science project (RMZ) ensures that both initiatives reinforce each other: MOMSTER lowers the threshold for students to engage with radio meteor observations through direct data collection, while RMZ offers an accessible

Table 1. Practical lessons and adaptations from MOMSTER's development.

Lesson area	Key insight	Practical adaptation
Student engagement	Authentic, hands-on data collection increases motivation.	Provided mobile kits allowing real meteor detection in schools.
Teacher autonomy	Complex technology limits classroom use.	Simplified setup with pre-configured laptops and two-button operation.
Curriculum integration	Clear links to learning goals boost adoption.	Connected each module to national curriculum standards.
Interdisciplinary flexibility	Inquiry-based learning enables broader curricular links by adding observational methods, connecting topics like geography to mathematics and data analysis.	Developed a modular educational buffet across STEM subjects.
Misconceptions	Students hold persistent misunderstandings about meteors and radio detection.	Addressed misconceptions explicitly in lesson materials and activities.
Partnerships and outreach	Collaborations extend impact beyond pilot schools.	Partnered with science outreach partners for wider visibility.
Logistical challenges	Scaling up introduces technical and operational hurdles.	Improved hardware durability, transport solutions, and support materials.

route to participate in authentic research. As noted by Finger et al. (2023), such hybrid models challenge traditional definitions of citizen science, because their educational value lies not only in the scientific utility of the data but also in fostering scientific agency and conceptual understanding. In this light, MOMSTER acts as an educational extension that can be seamlessly connected to RMZ, bringing new participants to the platform while strengthening classroom inquiry through a real-world scientific link.

Within the broader Belgian meteor observation landscape, other initiatives play complementary roles. The FRIPON-BE project is part of the international FRIPON network using optical all-sky cameras to detect bright meteors, reconstruct their trajectories, find their origin, and, where possible, support meteorite recovery by organizing field searches with citizen scientists (Colas et al., 2020). In contrast, the MOMSTER kit is based on the BRAMS forward-scatter radio network, which primarily detects the much more numerous faint meteors that do not produce meteorites. This makes it particularly well suited for classroom investigation of meteor occurrence patterns and atmospheric phenomena. Taken together, FRIPON-BE focuses on bright events of research interest, whereas MOMSTER enables students and teachers to engage with the broader meteor population and develop inquiry-based STEM understanding.

The development and classroom deployment of MOMSTER revealed a range of practical insights on how to implement STEM learning in secondary education. Table 1 summarises the core lessons learnt and the adaptations made in response, offering guidance for similar initiatives in astronomy outreach and beyond. The design choices and refinements summarised above set the stage for evaluating the broader education impact of MOMSTER, described in the next section.

4 Didactical analysis and lessons learnt

The MOMSTER project demonstrates how a school-based inquiry-based learning initiative can produce meaningful educational outcomes. Through iterative development, classroom deployment, and partnerships with educators and outreach institutions, MOMSTER achieved impacts across student motivation, teacher confidence, curricular integration, and public engagement.

In this section, we interpret these observations through a didactic lens, highlighting how MOMSTER's design features support learning. To anchor this analysis, we briefly situate MOMSTER within established models of inquiry-based learning. According to Pedaste et al. (2015), meaningful inquiry typically progresses through phases of orientation, conceptualisation, investigation, conclusion, and discussion. MOMSTER's activities map naturally into this cycle: students begin by exploring authentic spectrograms (orientation), formulate expectations about meteor occurrence (conceptualisation), collect and analyse data (investigation), draw evidence-based explanations (conclusion), and present their reasoning (discussion). These design elements situate MOMSTER firmly within established frameworks for effective IBL.

4.1 Boosting student engagement through real science

By giving students the opportunity to detect and analyse genuine meteor events using dedicated hardware, MOMSTER delivers an authentic scientific experience. Even if not intended for scientific publication, the data reflect real atmospheric phenomena, bridging the gap between education and research. Teacher feedback suggested that students showed increased curiosity, asked more questions, and were more engaged when interacting with live data.

From a didactic perspective, authenticity plays a central role: it provides a meaningful context for inquiry, encourages students to take an active role in making sense of data, and helps students recognise the relevance of scientific concepts. These observations align with research indicating that student motivation and ownership improve when students engage in real-world science (Kloetzer et al., 2021). According to Goździk et al. (2021), participation in authentic research contributes not only to knowledge acquisition but also to the development of critical thinking and scientific agency (students' ability to participate meaningfully in scientific practices and to see themselves as contributors to the scientific process). MOMSTER leverages this mechanism by embedding authentic data at the start of the inquiry process.

4.2 Towards modular and interdisciplinary teaching

The MOMSTER project offers subject-specific educational packages that allow teachers to select materials suited to their course context. This flexibility has proven essential for adapting the project to available time and learning goals. The observed diversity in the way the materials are used highlights both their adaptability and the broad disciplinary potential of meteor sci-

ence. The authors aim to further modularise the content to improve this flexibility and to move closer to a true educational buffet.

From a pedagogical standpoint, the interdisciplinary design is not merely organisational but serves a didactic function: it allows students to approach the same phenomenon (a meteor echo) through multiple disciplinary lenses, each contributing a different representational or explanatory tool. The interdisciplinary potential of MOMSTER does not stem only from the topic of meteors (often introduced in geography), but also from the observational method: radio signal analysis. This combination opens up broader curricular connections, including mathematics and physics, where students analyse and interpret their own observations.

Engaging with the same data across subjects helps students apply the ideas learnt in one context to another and shows how different disciplines work together in scientific problem-solving. As Lüsse et al. (2022) point out, interdisciplinary approaches that connect science to the larger learning contexts of students are more likely to achieve sustained learning outcomes. This is further supported by Bastiaenssens et al. (2022), who recommend flexible design—where teachers adapt externally developed content to fit their own goals and classroom needs—as a key enabler of IBL in schools.

In practice, the modular structure has proven essential for teachers to tailor MOMSTER to their available time and learning goals. Some used a single physics lesson on meteor velocity, while others combined geography and mathematics to examine meteor trajectories. These varied applications show how modular design can support interdisciplinary reasoning through structured guidance, without imposing it.

4.3 Supporting teacher autonomy and curricular fit

Another important factor in MOMSTER's success was the way it responded to the needs of educators. Teachers face time constraints, have varying levels of technical confidence, and must comply with government-driven learning standards. MOMSTER addressed these barriers by offering a plug-and-play kit, a simplified user interface, a dedicated laptop with minimal setup, and classroom-ready lesson plans.

These design choices not only reduce practical barriers, but also serve a didactic purpose: by minimising the mental effort required to operate the technology, teachers can focus on facilitating inquiry rather than managing equipment. This level of support helped teachers feel confident using the system independently, even with limited prior experience. As Müller et al. (2025) highlight, the availability of ready-to-use materials is a critical factor in ensuring that citizen science projects are adopted in formal educational settings. MOMSTER exemplifies how technical simplification can expand pedagogical uptake.

4.4 Integrating inquiry-based learning with citizen science

Although MOMSTER remains an inquiry-based educational initiative rather than a citizen science project, its structural link to RMZ (see Section 3.3) offers a layered approach: students engage in classroom-based observation and analysis, with the option to contribute to ongoing scientific research via the citizen science platform.

This hybrid design extends the inquiry process beyond the classroom. After interpreting their own (non-calibrated) observations, students encounter research-grade BRAMS data on RMZ, prompting them to compare data quality, classification criteria, and the rigour required for scientific publication. This progression, from personal observation to participation in a shared scientific workflow, helps students appreciate how scientific knowledge is built and how explanations emerge from collective data practices.

To our knowledge, this model of linking an inquiry-based school project with an external citizen science initiative is unique. It enables educators to maintain curricular alignment and hands-on experimentation within formal education settings, while still offering students an entry point into public research. We propose that such hybrid models, where formal education is meaningfully connected to citizen science, deserve further exploration as a strategy to bridge classroom learning and real-world science.

4.5 Engagement beyond the classroom: outreach and school uptake

MOMSTER was developed primarily for classroom use, but the project is also featured in public outreach activities such as science camps, open house events, and public lectures. These moments provide additional visibility and informal involvement with radio meteor detection, though they mainly attracted audiences already engaged, such as science enthusiasts and amateur astronomers. However, such events often attract science teachers, offering opportunities for them to discover MOMSTER and introduce it in their schools (Müller et al., 2025).

Based on our experience, the classroom context remains the most inclusive setting, offering access to younger and more diverse learners. To strengthen school participation, the MOMSTER team partnered with science education organisations (see the paragraph about partnerships and scaling in Section 3.2) that helped connect the project to new schools and align it with educational needs.

It remains to be evaluated how different forms of outreach, including public events, teacher trainings, and dissemination through educator-focused websites and magazines, contribute to further uptake in schools. Tracking how teachers discover the project could help improve future engagement strategies. Since these outreach activities have not yet been systematically evaluated, their educational impact remains to be assessed (see Section 5.2).

5 Conclusions and future perspectives

The MOMSTER project demonstrates how inquiry-based STEM education can serve as a powerful bridge between professional research and formal learning. By providing students and teachers with access to real scientific instruments and data, it enables authentic engagement with scientific processes and introduces participants to the broader context of citizen science.

5.1 Key insights from implementation

Several practical and pedagogical lessons emerged from the development and classroom use of the MOMSTER kit:

- **Technical accessibility and support:** Simplifying the setup of hardware and software, along with providing user-friendly documentation and responsive support, proved essential for teachers to confidently adopt the system.
- **Curriculum alignment and modularity:** The modular and interdisciplinary design of the educational resources allowed integration in a variety of subjects and student profiles. Explicit alignment with national curriculum objectives further supported the adoption of MOMSTER within formal education settings.

- **Interdisciplinary connections:** The use of radio observations enabled curricular connections beyond geography, notably to mathematics and physics, helping address the common under-representation of mathematics in integrated STEM projects (Portillo-Blanco et al., 2024).
- **Bridging education and citizen science:** Although the MOMSTER kits themselves do not generate research-grade data, the referral to the RMZ allowed students to participate in a real research process, lifting (at least partially) the trade-off between educational simplicity and scientific authenticity.
- **Sustainability and outreach partnerships:** Collaborations with outreach partners (e.g., observatories and science centres) helped relieve pressure on the core research team by sharing responsibilities related to logistics and support. While these partnerships likely contributed to increased visibility and school uptake, their impact has not yet been systematically evaluated.

5.2 Future directions

A key priority for future work is to strengthen the empirical basis of the project's educational impact. So far, indications of increased student interest and participation are based mainly on anecdotal teacher feedback and informal observations during lessons and public events. To substantiate these claims more rigorously, future iterations of the project will include structured evaluation, such as short pre- and post-activity student questionnaires, systematic teacher reflection forms, and classroom observations focussing on inquiry processes and conceptual understanding. This will help establish a clearer empirical foundation for assessing the educational impact of MOMSTER.

As a next step, we also plan to explore the potential for international expansion of the project. This expansion could strengthen the connection between classroom-based activities and the RMZ, potentially increasing public engagement with meteor science and supporting the classification of a larger volume of data. However, achieving these benefits will require careful adaptation to local educational contexts and technical infrastructures. Strengthening this link between classroom inquiry and citizen science remains a core motivation for future extensions of the project.

On the technical side, this includes identifying a suitable radio transmitter operating in the correct frequency range, with sufficient signal stability and proximity for effective detection. The antenna design must also be adjusted to match this frequency. On the educational side, curriculum alignment needs to be reassessed: Are the activities compatible with national education standards and learning objectives? Are existing materials culturally and pedagogically transferable, or do they need to be revised? Future pilot implementations in other countries will help evaluate the scalability and adaptability of the MOMSTER project.

5.3 General reflection

The MOMSTER project offers a replicable model for integrating inquiry-based STEM education with elements of citizen science in formal school contexts. Its design — which combines authentic observation, modular lesson materials, and optional pathways to real data classification — can inform similar efforts in astronomy education and beyond.

A notable contribution of MOMSTER lies in its hybrid structure, which connects a classroom-based inquiry activity with an external citizen science initiative (RMZ). This arrangement allows teachers to maintain curricular alignment and hands-on experimentation within formal education, while still offering students an authentic pathway to contribute to ongoing scientific research. Such hybrid models, where formal education is meaningfully linked to citizen science, merit further exploration as an approach for bridging classroom learning and real-world scientific practice.

The lessons learnt here may guide future initiatives seeking to balance scientific authenticity with classroom feasibility and curricular fit.

6 Availability of supporting data and materials

The educational materials supporting the findings presented in this article are available in the KU Leuven Research Data Repository:

Calders, Stijn (2025). "MOMSTER: teaching modules on meteors and radio astronomy for secondary schools". KU Leuven RDR. (DOI: https://doi.org/10.48804/AROQLD)

This repository contains the full set of MOMSTER educational modules in French, including lesson plans, student worksheets, and teacher guides. These materials correspond to the educational buffet described in Section 3 and are designed to support interdisciplinary teaching of meteor science and radio detection in secondary schools.

The archived version in the KU Leuven repository is frozen in time to reflect the content as described in this article. A continuously updated ("living") version of the materials is available online in both French and Dutch at:

- `https://momster.aeronomie.be/fr/materiel-pedagogique`
- `https://momster.aeronomie.be/nl/educatief-materiaal`

7 Declarations

7.1 List of abbreviations

- **BIRA-IASB:** Royal Belgian Institute for Space Aeronomy
- **BRAMS:** Belgian RAdio Meteor Stations
- **BRITEC:** Bringing Research InTo thE Classroom
- **ESERO:** European Space Education Resource Office
- **FRIPON:** Fireball Recovery and InterPlanetary Observation Network
- **IBL:** inquiry-based learning
- **IPF:** International Polar Foundation
- **MOMSTER:** MObile Meteor STation for Education & outReach
- **RMZ:** Radio Meteor Zoo
- **STCE:** Solar-Terrestrial Centre of Excellence
- **STEM:** Science, Technology, Engineering and Mathematics

7.2 Consent for publication

Karolien Lefever, recognisably depicted in Figure 7 while presenting the MOMSTER project, provided written consent by e-mail to the main author on 26 June 2025 for publication of this image.

7.3 Competing Interests

The authors declare that they have no competing interests.

7.4 Funding

This project was funded by the Europlanet Public Engagement Funding Scheme (2020 call) and the Solar-Terrestrial Centre of Excellence (STCE).

7.5 Author's Contributions

- **Stijn Calders**: conceptualization, investigation, writing - original draft
- **Hervé Lamy**: conceptualization, funding acquisition, supervision, writing - review & editing
- **Mieke Sterken**: conceptualization, writing - review & editing
- **Katrien Kolenberg**: conceptualization, supervision, writing - review & editing

8 Acknowledgements

The authors gratefully acknowledge the valuable contributions of Karolien Lefever, Michel Anciaux, and Antoine Calegaro (BIRA-IASB); Anne-Lize Kochuyt, Hans Coeckelberghs, Judith Vandewiere, and Charly Mobers (Brussels Planetarium); Maya Boueiz (InforSciences at Université Libre de Bruxelles); Koen Geukens (public observatory Urania); and Coralie Byttebier (Euro Space Center), whose support and collaboration were instrumental to the success of the MOMSTER project.

We also thank Wim Van Buggenhout for his contribution to the development of the geography education package, and Alex Calders for co-developing the geometry exercise on meteoroid trajectory reconstruction. Further thanks go to Rune Dillen, Margot Nys, and Natacha Gesquière for their constructive feedback on the educational materials.

Joachim Wuytjens, employed as a student worker by the IPF during the summer of 2023, reviewed all educational packages with the aim of enriching their content and aligning them with extracurricular learning objectives.

Finally, the lead author wishes to thank Patrick Vanouplines for kindly proofreading the manuscript prior to submission.

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