Which observatories for PCMI?

Summary by Jérôme Pety, Karine Demyk, Ludovic Biennier, and Patrice Theulé, on behalf of the PCMI community

15 March 2022

Web site: https://pcmi-observ-21.sciencesconf.org/

Youtube playlist: https://www.youtube.com/playlist?list=PL_NFSbJZUb8hIFyep_JJOLSLJ-EzIj9mO

The observational data gathered by state-of-the-art astrophysical facilities provide our primary source of information towards a better understanding of the impact of the interstellar medium physics and chemistry on high redshift galaxies, on star and planet formation in the Milky Way, or on life emergence. Opening up new regions of discovery space through increased sensitivities, angular and spectral resolutions, polarimetry, survey speeds, multi-wavelength multi-carriers studies is essential to understand these fundamental questions of astrophysics.

This 4-day workshop first aimed at mobilizing the community on the observatories under construction or evolution and on long-term research and development activities, both for ground and space observatories. It also aimed at defining the scientific challenges of the PCMI community within the next 5-15 years to define the space of parameters to be explored and the associated observatory characteristics.

This document summarizes the main information gathered during the workshop on the following observatories and technologies: The Athena X-ray satellite; Infrared, optical, and UV observatories; Sub-mm and millimeter ground-based observatories; The Square Kilometer Array; Radio-astronomy wide-field, wide-bandwidth imaging; Continuum polarimetry, low resolution spectroscopy in FIR and (sub)mm; FIR/(sub-)mm spectroscopy; Simulations vs observations; Electronics & Software in an era of big data. The detailed workshop program is available in appendix A with individual links to the associated video recordings.

ATHENA workshop

The Advanced Telescope for High ENergy Astrophysics (ATHENA) is an ESA class L mission to be launched in the early 2030s. This space observatory in the soft X-rays wavelength range (0.1 eV -12 keV) will be equipped with two instruments: the Wide Field Imager (WFI) and the X-ray Integral Field Unit (X-IFU). It will probe the hot and energetic Universe with unmatched sensitivity and precision. The ATHENA mission will provide a better understanding of the formation and evolution of hot baryonic matter large-scale

structures, as well as the black holes growth mechanisms, especially in the young Universe. The ATHENA mission will also make it possible to study the gamma-ray bursts as well as the coupling of stellar winds to planetary atmospheres and magnetospheres. These energetic phenomena are coupled with the interstellar matter of the host galaxies (structures in filaments, polarization, accretion disk, matter ejection, galactic fountain, metal enrichment). The ATHENA mission will contribute to giving a multi-wavelength (by association with SKA, ALMA, NOEMA, ELT, JWST, ...) and multi-messenger (by association with LISA) vision of our Universe.

The PCMI community has many scientific interests that will benefit from ATHENA observations (e.g., studies of the multiphase ISM: dynamics of the hot ionized medium, coupling and mixing between the hot, warm and cold phases, impact of the dust on the hot gas cooling, sputtering processes of dust grains in the hot plasma, elemental abundances, e.g., Mg, Si, O, Fe, Al, Ca, S). PCMI also has a strong expertise in Laboratory Astrophysics that will provide insights for the interpretation of ATHENA observations. This encompasses the interaction of matter (interstellar ices, carbonaceous dust, silicates) with X-rays and the spectroscopic characterization of dust analogs in the X-ray domain.

The community needs to prepare itself to take full advantage of the exploitation of this new facility and different routes have been identified for this. It has been proposed to create a working group gathering a few members of the PCMI community and from the ATHENA instruments in France. Its goals will be to examine the feasibility of observations of some specific use cases of interest for the PCMI scientific themes.

Infrared, optical, and UV observatories

JWST

The PCMI community is highly engaged in the James Webb telescope that was successfully launched on the 25th December 2021 with, for instance, the PIship of one ERS program, the co-Piship of the MIRI GTO program on PDRs and in the MIRI commissioning as well as via Laboratory Astrophysics and modeling works to support the interpretation of the data. However, French scientists under-subscribed to cycle 1 proposals. All communities, including the PCMI one, need to be much more strongly implicated in cycle 2 proposal (expected deadline: January 2023) to get a fair return from the instrumental investment. The community is encouraged to use the service proposed by MICE (The MIRI expertise center: https://www.jwst.fr/expertise-centre-general/).

ELT and VLTI

Complementary to the JWST, the construction of the ELT is on-going and the first light instruments are expected end of 2028, among which several are of interest to PCMI (the MIR spectrometer METIS as well as the NIR integral field spectrograph HARMONI, the VIS/NIR multi-object spectrograph MOSAIC and the second generation high resolution spectrograph HIRES in the NIR). JWST and ELT instruments are fully complementary with extreme sensitivity for JWST versus high spectro-angular resolution for ELT. ELT instruments will combine high spatial and spectral resolution in a range full of key dust features and warm gas diagnostics that will constrain the location of the emission in compact objects (e.g.

inner disks, center of galaxies, etc) and understand the dynamical processes. The VLTI already offers interesting opportunities for some PCMI scientific questions such as the cycle of matter in circumstellar environments. The PCMI community is encouraged to prepare for the exploitation of the ELT by actively using the currently available instruments. PCMI will continue to co-organize the ELT workshops during the annual meetings of the SF2A in order to keep the community informed.

Visible and optical

The NASA Astro 2020 Decadal Survey recommends a large (JWST-like) aperture IR/VIS/UV space telescope that combines most of the capabilities of proposed missions LUVOIR and HabEx. Such a mission will need to first go through a phase of technological maturation throughout most of the 2020 decade with a launch date around the end of 2030 decade. The optical and UV domains are fundamental to PCMI science cases related to chemistry, dynamics, and possibly polarization through emission- and absorption-line spectra probing HII regions and the diffuse ISM in every phase (including the molecular phase with H_2, CO, CH, etc). The spatial resolution is also designed to enable access to protostellar and protoplanetary disks with multi-object spectrographs. The recommended mission would provide a factor 10 better sensitivity in the optical domain compared to the ELT and several orders of magnitude in the far-UV compared to previous missions. As such, it would be a huge opportunity in order to provide breakthroughs as major as the HST. Given the present difficulty in accessing the UV domain and the corresponding difficulty in structuring the UV community, it is important that the PCMI community anticipates and organizes potential applications, especially if European/French instruments can be implemented.

IR Research & Development

New generations of large, very low noise infrared detectors are currently being investigated. They could be combined with new concepts of high resolution spectrometers or spectro-imagers using novel interferometric components. Moreover, the fast developments of quantum technologies renew the research around mid-infrared high resolution heterodyne spectroscopy technologies. Combined with long baseline interferometry, these could provide aperture synthesis at high angular resolution and spectral resolution.

(sub-)mm ground-based observatories

NOEMA and ALMA

The NOEMA project on plateau de Bure will be fully operational at the end of 2022 with 12 antennas, baselines up to 1.7 km, and either A) 32 GHz bandwidth at 250 kHz spectral resolution, or B) 32 GHz at 2 MHz spectral resolution plus a quarter of this band in 128 spectral windows at 62.5 kHz resolution, in order to simultaneously observe the continuum emission and target specific lines at high spectral resolution with a large flexibility of choice. The dual frequency extension that will follow before the end of 2023 will double the available bandwidth from 32 to 64 GHz.

The ALMA Roadmap 2030 was presented including the on-going technical developments to broaden the receiver IF bandwidths and upgrade the associated electronics and correlator. In addition, longer-term propositions were mentioned such as increasing the collecting area by adding up to thirty 12-m antennas to the baseline array. Additional antennas will significantly impact all the new ALMA science drivers, bringing numerous operational and imaging capabilities with large science benefits.

The 30-50 GHz range, which will not be covered by SKA, is important to complete the inventory of heavy molecules in the interstellar medium, as recently shown by results obtained with the 31-50 GHz receiver installed at the Yebes 40-m telescope. This highlights the value of having these frequency ranges available in other existing facilities (e.g. NOEMA). This frequency range will be available with the Band 1 of ALMA, which will be offered for open-use observations in Cycle 10, starting in October 2023. The next generation VLA, supported by the US 2021 decadal review, could also cover this frequency range.

IRAM-30m and APEX

The IRAM 30 m telescope will be refurbished during the summer 2022. The electronics of the antenna control will be upgraded to comply with current standards and the primary surface will be repainted. The NIKA2 continuum camera allows astronomers to image a wide field of view at 1 and 2 mm, with a polarimetry mode at 1 mm. Prototypes of heterodyne multi-beams receivers at 1 and 3 mm are ready to be tested on the sky.

The APEX 12m submillimeter telescope has been operating since 2004 in Chajnantor by three partners (MPIfR, ESO and OSO). Major antenna refurbishment and instrument upgrades have been ongoing in the past years and by now, state of the art heterodyne and continuum instruments are available in the range of 150 GHz to 850 GHz (about 8-10 instruments are available). The French community has built and installed the ARTEMIS continuum camera and the CONCERTO low spectral resolution camera. As ESO and OSO will drop their participation in 2022 the telescope will be exclusively funded by MPIfR until the end of 2025. At this stage, it is unclear whether it will be prolonged afterwards. Consequently, CONCERTO should stop observations after December 2022.

Single dish wide field mapping

Sub-millimeter to cm instruments are going both wide-field and wide-bandwidth with a high spectral resolving power. In the (sub-)millimeter domain, the technology is ready to build multi-beams of several tens to one hundred beams, each covering a minimum of 16 GHz of bandwidth with a typical resolution of 200 kHz. The main challenge is to raise the funds to build such instruments. These will lead to science game-changers. For instance, a 49 beams operating at 3 mm during about 1000 hrs would either allow one to cover a significant fraction (125 square degrees) of the galactic plane at a good sensitivity (0.1 K) or to cover a significant fraction (5 square degrees) of a nearby Giant Molecular Cloud at an excellent sensitivity of 25 mK! It will thus be possible to make sensitive line surveys over millions of lines of sight.

The AtLAST project is a 50m single-dish telescope that would operate in the sub-millimeter at Chajnantor. This project also aims to bring wide-field imaging to a new dimension with a

potential field-of-view of 2 square degrees. This design study is taking over the many challenges associated with such an ambitious project. This will allow the team to make a better cost estimate before touring the world to raise fundings.

As a pathfinder, the Fred Young Sub-millimeter Telescope (FYST) is a US/Canada/German project (FYST), consisting of a 6m telescope with a 1 square degree field of view located at 5260 m in Chajnantor. Its first light instruments are aimed at making wide-field surveys in continuum and lines. While this is a PI instrument, the German partner welcomes external collaborations.

Future intermediate-size projects

The ALMA increase in the number of antennas or the AtLAST telescope belongs to the 0.5 billion dollar level projects. Intermediate-size projects should also be considered. With the completion of the NOEMA project, IRAM is ready to undertake new instrumental challenges for the coming decade. This can be either done by developing wide-field imaging with large multi-beams first at Pico and then at Bure, and/or adding new antennas to the NOEMA array.

The advent of the KID technology opens the possibility to do sensitive continuum, polarimetry, or low resolution spectroscopy (aka, line photometry) on ground-based telescopes. The number of pixels currently reaches many thousands, and it continues to increase quickly. A possible project is a 15m dish (à la NOEMA) that could cover, in 10 years, the whole Northern sky, with sub-arcminute resolution in the millimeter domain (1-3 mm) with a wide-field instrument (40 000 Kids), and polarimetric and spectroscopic options. The cost of the project is around 20 millions euro (plus the operation cost). This project would be a useful complement to Planck low angular resolution whole-sky maps for many PCMI topics.

Airborne Far Infra-Red and submm

The FIR/(sub-)mm is widely used by the European astronomical community, and especially, the PCMI community. The sub-mm spectroscopy can be carried out from ground, routinely up to ~350 GHz, and up to 1 THz from excellent sites (see submm ground-based observatories). While airplanes, balloons or satellites are required, the space future FIR spectroscopy is currently unclear.

Spectroscopy

The SOFIA airplane carries the upGREAT instrument among others, but its future is uncertain. On one hand, there is a plan to upgrade the heterodyne instrument to 100 pixel heterodyne arrays. On the other hand, NASA considers shutting down the SOFIA operation in a couple of years. CNES specializes in short (hours to 1 day) balloon flights. The NASA balloons with up to 3 months flight duration are more suitable for astronomical observations requiring lengthy instrument development. The balloon-borne facility ASTHROS (https://www.jpl.nasa.gov/missions/asthros) aims to map different regions of the sky in [NII] at 205 μm, [NII] at 122 μm, and [HD] at 112 μm, with a heterodyne spectrometer. Other balloon-borne missions are proposed such as GUSTO ([NII] at 205 μm, [CII] 158 μm, and [OI] at 63 μm, https://www.sron.nl/missions-astrophysics/gusto) or co-PILOT to map the [CII]

cooling line in our Galaxy and in nearby galaxies. However balloon-born missions and aircraft are focussed on specific science cases and observe a small fraction of the sky and cannot replace a large space observatory such as Herschel.

Continuum and polarimetry

Polarimetry is now a mature technology. It is opening the possibility to study magnetic fields in the Universe. The LiteBIRD project will aim to measure the imprint of the inflation era in the B-modes of the Cosmic Microwave Background. To do this, new studies of the dust polarimetry properties from the interstellar foregrounds is required. LiteBIRD will thus deliver fundamental information on the dust population in our Milky Way. It is important that the PCMI community continues to actively support LiteBIRD in a context of a tense budget at CNES.

Current and future opportunities

The removal of SPICA has left the European community without clear perspectives on Far IR polarimetry. The US decadal survey has classed an IR/VIS/UV telescope as a first priority for a large mission for launch in 2045, with recommendations for an infrared and an X-ray missions thereafter. In the meantime, it also recommends a probe size mission (1G$) either in infrared or X-rays for launch in 2030. A call will be issued early 2023. Europe should be prepared to potentially join and improve the capabilities of such a project. In the far-IR, four different far-IR concepts (PRIMA, FIRSST, SPIRIT, SALTUS) are being prepared. All four concepts are still being defined. PRIMA focuses on following the evolution of star-forming galaxies from the dark ages to the present time, FIRSST is tracing the trail of water during star and planet formation as well as galaxy evolution, SPIRIT is an interferometer to image proto-planetary disks with direct detection cameras, and SALTUS is a large inflatable telescope to also observe proto-planetary disks but with heterodyne receivers.

Finally, ESA currently has a call for M7 (with a phase-1 proposal deadline: 14 Feb 2022; a phase-2 proposal deadline: 14 July 2022; and a selection by november 2022). Several far-IR missions are proposed, including a mission (LETO) to map the Galactic plane, some nearby galaxies and a blind survey in the main cooling lines (e.g., [CI] at 370 μm, [CII] at 158 μm, [NII] at 205 and 122μm and [OI] at 63 μm).

SKA

France joined the SKA organization mid-2021. The construction phase of the SKA observatory started in July 2021, with an expected end in 2028. France has one of the largest and most active ISM communities in the SKA consortium, providing real opportunities to lead ISM Key Science programs. In this context, the community is encouraged to engage in current SKA Science Working Groups and to join forces to define Key Science programs on interstellar studies (https://astronomers.skatelescope.org/science-working-groups/). Milky Way interstellar studies with SKA will require dedicated short-spacings observations. Studies about the way to get them exist but the PCMI community has to lobby to convert these plans into actual developments.

With SKA a large breath of new observational probes relevant to PCMI is becoming available (21 cm, radio recombination lines, synchrotron, Faraday rotation, free-free and dust emission from cm size grains...) with a large range in spatial scales, arcsecond resolution, and high sensitivity. Before SKA first light, several precursors are operational, including MeerKat that will be included in the SKA-mid telescope, providing an efficient way to define future SKA science programs. The community is invited to exploit these SKA precursors (MeerKat, LOFAR, ASKAP, MWA, ...), and contribute to the definition of innovative techniques needed to address the challenges associated with the analysis of large radio data sets. More information is available at https://as-ska-lofar.fr/. A complementary facility will be the NSF funded DSA2000 project.

Astrochemistry and star formation studies will benefit from the high angular resolution and sensitivity of SKA, which are highly complementary to mm and sub-mm observations in order to (i) detect and study heavy carbon-chain and cyclic hydrocarbon molecules at lower frequencies, and (ii) to investigate the chemical complexity of young warm embedded objects without being obscured by dust opacity effects and, consequently to retrieve real chemical abundances.

Simulations vs observations

Both observations and simulations are delivering big datasets that contain exquisite details on the numerous processes at play in the formation of stars in the interstellar medium. Several challenges will have to be tackled over the next decade. First, simulation algorithms will have to be adapted to heterogeneous giant computation and data centers to use them optimally. Second, simulations, modelisations, and observations, all have their own limitations. It is thus needed to develop new tools to improve the comparison between these three fields. These tools will probably have to finely characterize the statistical nature of the interstellar medium observations. Machine learning technologies will probably help us to improve our capacity to classify data in low signal-to-noise regimes.

Electronics & Software in an era of big data

New observatories will produce data rates much larger than what can be saved on disk. However, the advent of the FPGA and GPU technology enables us to start thinking about encoding calibration algorithms in the backend part of the telescope. This will allow us to integrate the data on long timescales and thus reduce the final data rate. This is a major conceptual change of the observations as it could in part remove our ability to recalibrate the data offline.

Efficient software will be needed to be able to deal with both large data sets and collections of heterogeneous (continuum, line, polarimetry, at different wavelength) data sets in a single astrophysical analysis. Legacy FAIR (Findable, Accessible, Interoperable, Reusable) databases are now a common product of observatories. We need new software to be able to easily browse them to understand whether it is worth downloading the data.

Appendix A: Detailed program

Monday October 18th

- 09h30-09h50: P. Laudet, Introduction

09h50-11h30 X-ray Observations

- 09h50-10h20: D. Barret, The Athena X-ray Observatory
- 10h20-10h40: P. Cristofari, The very-high-energy gamma-ray domain and ATHENA
- 10h40-11h10: D. Porquet, X-ray observations of radio-quiet AGN and outflows
- 11h10-11h30: T. Zafar, Gamma-ray bursts at X-ray wavelengths

13h30-15h00 X-ray / Matter Interaction

- 13h30-14h00: E. Dartois, Matter-radiation interactions in the X-ray rwavelength range in laboratory
- 14h00-14h20 E. Costantini, The chemistry of interstellar dust at high resolution with Athena
- 14h20-14h40: J-H. Fillion, Experimental investigation of X-ray irradiation of interstellar ice analogs with synchrotron radiation
- 14h40-15h00: F. Rosmej, The principles of non-Maxwellian and non-stationary atomic kinetics driven by suprathermal electrons and intense photon sources

15h30-16h20 ISM Energetic Phenomena

- 15h30-16h00: A. Gusdorf, ATHENA and the Galactic interstellar medium
- 16h00-16h20: G. Yang, CIGALE: Fitting AGN/galaxy SEDs from X-ray to radio

16h20-17h20: Round table

Tuesday October 19th CNES, Salle de l'Espace - Les Halles, Paris

08h30-10h50 IR observatories

- 08h30-09h00: P.O. Lagage, Status and scientific goals of JWST
- 09h00-09h30: E. Habart, Status and scientific goals of ELT and VLTI
- 09h30-10h00: J.P. Berger, Prospective on infra-red R&D
- 10h30-10h50: B. Tabone et al., Unveiling the chemical and physical structure of planet-forming disks with future infrared facilities: the case of oxygen chemistry

10h50-11h50 Dust and PAH

- 10h50-11h20: D. Marshall, Current state and future of 3D extinction mapping
- 11h20-11h50: O. Berne, Prospective on PAH studies

13h50-14h40 Optic / UV constraints on ISM

- 13h50-14h20: V. Lebouteiller, Status and scientific goals of LUVOIR
- 14h20-14h40: A. Nanni, The build-up of metals and dust in the Universe: constraints from local dwarf galaxies and lyman-break galaxies at the epoch of reionisation

14h40-15h10 Round Table "Optic / UV / IR constraints on ISM"

- 15h40-16h00: G. Perrin, INSU viewpoint

16h00-16h50 Astrochemistry

- 16h00-16h30: C. Engrand, Status and scientific goals of sample return missions
- 16h30-16h50: M. Bouvier, Unraveling the Sun's chemical past

16h50-17h40 Wide-field, wide-bandwith imaging

- 16h50-17h20: C. Risacher, Prospective on multi-beam detectors
- 17h20-17h40: J. Pety et al., Millimeter rotational lines as powerful diagnostics of the physical conditions of the molecular gas

Wednesday October 20th

- 08h30-08h50: M. Gerin, IR and IR* at INSU

08h50-12h10 (sub-)mm ground-based observatories and science - IRAM/ALMA/AtLAST/FYST

- 08h50-09h20: P. Cox, Prospective on future studies of the interstellar medium in galaxies near and far
- 09h20-09h50: K. Schuster, Prospective on (sub)-mm radio-astronomy
- 09h50-10h20: C. Cicone, AtLAST - The Atacama Large Aperture Submillimeter Telescope
- 10h50-11h10: T. Nikola et al., CCAT/FYST and its Science Goals
- 11h10-11h30: N. Schneider et al., The Galactic Ecology science case on CCAT-prime/FYST
- 11h30-11h50: M. Tahani et al., Mapping magnetic fields from kpc to core scales with FYST/PrimeCam large-area surveys of polarized dust emission

11h50-12h10 Round Table "Wide-field, wide-bandwidth and (sub-)mm ground-based observatories"

14h10-15h10 Stars and planets

- 14h10-14h40: A. Maury, Which challenges for the future studies of protostars and young proto-planetary disks ?
- 14h40-15h10: A. Lopez-Sepulcre & C. Ceccarelli, Prospective on molecular studies

15h10-16h00 Simulations vs observations

- 15h10-15h40: B. Commercon, Prospective on ISM and stellar formation simulations
- 15h40-16h00: E. Allys et al., What statistical metric to compare ISM simulations and observations?

16h30-17h40 Electronics & Software for big data

- 16h30-17h00: A. Randriamanantena, Prospective on electronics and signal processing R&D
- 17h00-17h20: J. Pety et al., Two current developments of the IRAM Science Software: OMS and CUBE

- 17h20-17h40: P. Salomé, ARTEMIX/YAFITS

17h40-18h00: Round Table "Stars and Planets, Simulations vs observations, Electronics & Software for big data"

Thursday October 21st

08h30-12h10 Continuum, polarimetry, low resolution spectroscopy - FIR and (sub)mm

- 08h30-09h00: L. Montier, Status and scientific goals of LiteBIRD
- 09h00-09h30: M. Sauvage, Perspective for ISM polarimetry science
- 09h30-09h50: P. Andre, Probing filamentary star formation and the role of magnetic fields on various interstellar scales with Millimetron-B-BOP
- 10h20-10h50: A. Monfardini, The role of KID in future millimetre and sub-millimetre instruments
- 10h50-11h10: F.X. Desert et al., Spectral studies of the interstellar dust submillimetre emissivity
- 11h10-11h40: A. Beelen, APEX/Concerto
- 11h40-12h00: Round Table "FIR/(sub-)mm continuum and polarimetry"

14h00-16h30 FIR/(sub-)mm spectroscopy

- 14h00-14h30: M. Wiedner et al., Status and scientific goals of OST and HSTDM
- 14h30-14h50: S. Madden, SOFIA Science Highlights and Future Roadmap Plans
- 14h50-15h10: L. Pagani et al., A TeraHertz Balloon-Borne facility: ASTHROS
- 15h10-15h30: N. Biver et al., Orbiting Astronomical Satellite for Investigating Stellar Systems (OASIS): following the water trail from the interstellar medium to oceans
- 16h00-16h30: P. Guillard et al., Observations of molecular hydrogen in space: perspectives with JWST and OST

16h30-17h40 SKA

- 16h30-17h00: M.A. Miville-Deschenes, Status of the SKA and prospects for interstellar medium studies
- 17h00-17h20: E. Bianchi, SKA for astrochemical characterization of Solar System precursors
- 17h20-17h40: M. de Simone et al., Unveiling the hot corinos nature combining mm and cm wavelengths: A new era with SKA
- 17h40-18h00: Round Table "FIR/(sub-)mm spectroscopy and SKA"