ISSI Forum on
“Ground and Space Astronomy: Challenges and Synergies”

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FINAL REPORT

Summary

The ISSI Forum on “Ground and Space Astronomy: Challenges and Synergies” took place on November 18 and 19, 2021, at ISSI Bern. The rationale behind this topic is the fact that fully achieving all scientific objectives of many space and many ground-based surveys increasingly relies on the combination of space data and ground-based observations. This is the case for ESA space missions aiming to characterize extrasolar planets, like Plato, but also for Galactic studies with Gaia, or cosmological missions like Euclid.

At this ISSI Forum, 25 international experts met in order to discuss these new challenges. Most of them could participate physically in Bern and around 20% joined online due to travel restrictions for non-European participants caused by the on-going pandemic. Underlying questions were: Which research areas would benefit most from combined space and ground-based data, either obtained simultaneously or at least with contemporaneous observing epochs? How is data best archived and made accessible for all users? Which process should be followed when selecting space missions and ground facilities to ensure their complementarity, while retaining their operational independence, priorities and competitiveness?

Four keynote talks on the “Science view” (by E. van Dishoeck), on the “Space-based view” (by F. Favata), on the “Ground-based view” (by B. Leibundgut), and on the “Exoplanet view” (by W. Benz) formed the backbone of the Forum. In addition, three special contributions were given on the Japanese experience (by S. Miyazaki, online), the Gaia experience (by T. Prusti) and the US perspective (by S. Kahn). Further short contributions from attendees were included as part of the discussions.

A very important and interesting part of the Forum were the lively discussions, including online participants across different time zones. These discussions gave a very broad and comprehensive overview of the challenges and synergies in collaborating between ground and space astronomy. Technical aspects were addressed, as well as “cultural” differences among the scientific communities, and particularly programmatic challenges.

At the end of the Forum, it was felt that this “kick-off” should be followed by suitable further activities, within IAU and COSPAR. These are already being prepared for their corresponding assemblies in 2022.

Introduction

Astronomy is currently advancing at a fast pace with the combination of data provided by space platforms and ground-based observatories covering the entire electromagnetic spectrum, as well as – more recently – by means of high-energy particles and gravitational waves.

The current development of very large ground-based observatories and very complex space missions requires considering the benefits of their complementarity for the overall sake of scientific excellence. It is thus important to review the potential synergies and the possibilities for cooperation, following the example of the new field of multi-messenger astronomy. It is, however, also necessary to identify the challenges for further advancement and to discuss how to mitigate potential problems and difficulties. Examples of the challenges to be addressed include the selection of missions considering all elements involved, exchange of information, coordination of mutual support, open data access, response to alerts, time allocation, guaranteed time and the definition of joint proposals.

Facilities in space are currently large and expensive, but the new ground-based large facilities also demand significant public resources. The identification of the big scientific questions, and how they are best addressed, should thus involve both space and ground-based projects through their respective roadmaps. The discussion of new elements and the establishment of long-term plans should ideally be formulated taking into account the full exploitation of both, which would demonstrate to decision-makers an efficient use of resources.

This ISSI Forum provides a platform to share ideas among astronomers to facilitate and encourage coordination in the preparation of astronomy roadmaps. It also seeks to identify opportunities for collaboration when it comes to the development, operation and data exploitation of the different ground and space-based observatories. Particular attention is devoted to the identification of difficulties in the development of joint activities and how they could be addressed and overcome by individual astronomers, national agencies or international entities.

The Science View (Keynote 1 plus contributions and discussion)

Space and ground astronomy need each other for many science goals to be achieved, thus opening the challenges. Good science can also be done stand-alone, but space and ground strengthen each other, thus producing synergies. A number of examples were shown of multi-wavelength and multi-messenger astronomy, as well as multidisciplinary science. An early example is the identification of GRBs in the optical with their host galaxies, despite the associated planning and scheduling challenges. More recently, a neutron star-neutron star merger, detected with gravitational waves, was identified with its high-energy source counterpart. A novel multi-messenger example is the Blazar with emission of neutrinos. Kavli-IAU workshops on transients are being held to discuss alerts, data policies, follow-up observations and telescope coordination.

An upcoming example of cooperation is the growth of the large-scale structure over the last 10 billion years, showing the impact of dark matter and dark energy. Weak lensing “cosmic shear” studies require “sharp” space missions as well as “deep” ground-based surveys, together with simulations to better understand baryonic feedback processes and selection biases. Combining data from JWST and ELT will allow astronomers to do galactic archeology, and to study the early history of young galaxies.

For the formation and evolution of the Milky Way, synergies between the ESA Cornerstone Mission Gaia and ground-based facilities carrying out large spectroscopic surveys have turned out to be extremely beneficial. Similar synergies are also being developed for studies of star and planet formation. Here special research topics requiring space- and ground-based high-resolution measurements, complementing each other, are the study of the origin of jets and outflows, and constraining the lifecycle of gas and dust in the context of planet formation. Probing protoplanetary disks opens a new era in observational planet formation and the possibility of making a chemical inventory of young low-mass stars. The characterization of extrasolar planets is also a demanding task. It requires space and ground facilities as well as the development of critical technologies and a whole new ballgame for exoplanet atmosphere modeling is expected, including the search for traces of life beyond Earth. (For more details see Keynote 4: The Exoplanet View)

Several questions were raised regarding the need for long-term coordination, including the possibility to propose joint space-ground missions. Ground facilities are seldom standing alone and it is important that the complementarity offered by them is not simply considered in a hierarchical way. Ground-based astronomy does not just pay service to the space missions.

In general, ground-space cooperation is going smoothly, with misunderstandings usually resolved in a fast way, when built around science synergies. This cooperation hinges on the resulting advantages for science, and often good personal connections. Open communication and trust are the most important criteria for the success of such collaborations.

It was also pointed out that international (space-ground) collaborations in astronomy are frequently subject to considerations related to return on investment in terms of observing time, data sharing, joint analysis, publications, authorship, etc. This is different to particle physics, e.g., at CERN, where collaboration is about the in-kind contribution of each participant. Again, personal relationships are critical, and trust is the main ingredient to address policy challenges and build bridges. Single telescopes may not be sustainable long term and changes in the model/philosophy of collaboration should be considered. Optical/NIR telescopes should seek coordination in instrumentation and, possibly, operations to have a higher impact. Space and ground facilities should work together to make the best out of the investments. The future of space astronomy is clearly affected by cooperation in the development of ground observatories. Duplication is not a problem, but the big gaps between space and ground facilities, for example in observing time, are a challenge. They may be detrimental in some circumstances and open opportunities for complementary in other. For example, why do we have only one real jointly studied case of GW source? We should have many more by now!

Why is it difficult to have competition and collaboration simultaneously? How do we ensure appropriate credit is given – to scientists, engineers, instrumentalists, etc. – if several thousand people contribute to a joint project, with funding coming from a variety of sources. Would it be possible to create joint space-ground panels for mission selection? In fact, members are usually the same, but problems may be the different time scales for the development of technologies, or optimization during the operations time.

In summary, most major questions in astronomy require a multi-wavelength or even multi-messenger approach. Space and ground facilities need/strengthen each other, and this implies that mutual requirements and commitments should be considered when they are selected/adopted. The community usually rallies quickly behind a big space project, working well together. The complementarity of ground-based data is often more fragmented due to the difficulty in getting large chunks of time on a single telescope for large surveys or (coordinated) time-domain observations. Open data and open archives are essential elements to be secured.

The Japanese experience, with the national telescope Subaru, was presented in attracting scientists and enabling synergetic programs with space missions. Provision of imaging data for the Euclid mission has been agreed, allowing preparatory scientific studies before launch. Subaru observing time is also foreseen for synergetic observations with the Nancy Grace Roman space mission (formerly called WFIRST)

While ground and space astronomy have had their respective independent plans, these have been highly complementary. An early exchange of information regarding the plans of the respective communities is becoming increasingly important to ensure the best scientific exploitation of large facilities. The US decadal surveys consider this aspect, but more international platforms may be needed to implement the bi-directional flow of information.

The Space View (Keynote 2 plus contributions and discussion**)**

ESA missions are selected without associated ground-based facilities. Scientific excellence drives the mission selection process, not the facilities used. However, the implicit assumption is that the ground-based facilities will become available. The Forum participants discussed the need to also include criteria relating to the availability of ground-based facilities when selecting ESA missions. Can we, in the future, propose a combined space-ground mission? There are few exceptional examples for synergies, like the Sloan Digital Sky Survey (SDSS) complement to space-based surveys.

There was a long and intense discussion about the usefulness of roadmaps. However, we have to distinguish between roadmaps without executive power and e.g., long-term planning of ESA Science programme documents, like Horizon 2000 or Voyage 2050. Roadmaps coming from the communities (involving e.g., hundreds or thousands of scientists) are also important to trigger research directions, visions incl. technology challenges, or keep the momentum high in a given direction, and it is one of the instruments for the scientists to raise their voice and to organize communities.

Collaboration must respect different cultures, sociology and diversities. An example may be ALMA where the willingness for science excellence is the key of success, with no personal ego influence. Scientists are supporting the mission's proposals, they are critical. In cases where they do not join forces among different groups, a 3rd party is the winner. Nugatory arguing is not the path to follow for international collaboration or proposing missions. For an endorsed mission, the willingness in coordination of a mission is critical (among others). In the mandatory ESA science program, the scientists select the missions and the roadmaps help to shape multi-disciplinarity and international collaborations and visions.

Science should drive the discoveries, and technology should be developed to reach the scientific visions. However, most of the time/money is not for science but for industry, but industry should not be the driver! A series of programmes/visions increase the interests of industry. The feedback from scientists to industry or government or private is critical, e.g., wifi or AI is coming from the science domain to the general use.

Open Data Policy (ODP) is still a problem for national funding agencies, „what do we get back?" is the main question/problem they ask. ODP works only if all the members are sailing in the same directions or play together as a team. NASA or ESA generally favor open data policies. However, it is specific to missions. Moreover, ODP is not just about data, but the tools/software/data reductions software/calibrations. The culture of free tools and data is still not commonly developed. ODP should become more popular to find new models between funding agencies and ODP agreements or interests. Public funded missions should lead to ODP. The culture is that the engineers and tools developers are working for 10-20 years to build the equipment and write the software, and they are working afterwards for maintenance; for them it is not in their culture to share for free. This implies a challenging change request in our culture.

The „Virtual Observatory" (VO) may be the future, unifying the data process standards. This nevertheless could be challenging since it may be perceived as a black box, and the data are not always directly usable for publications where calibration or a deeper knowledge of data analysis and instrument background is requested.

The experience of the Gaia mission was presented. Gaia has a consortium doing the data processing, but no data rights. Gaia is a survey mission, i.e., no pointed observations. But Gaia needs support from the ground-based facilities for calibration and spacecraft tracking. Ground based observations are needed, in combination with the space-based data, for the complete scientific exploitation and proper science follow-up.

A general challenge for all astronomical space missions (not Gaia-specific) is: How to secure the necessary calibration observations through various observing time allocation committees. There is no "glory" in calibration programmes, neither to the astronomers nor to the ground-based facility. Time allocation committees struggle on how to distinguish genuine calibration programmes ("this programme is also useful for Gaia calibration") and how to rank space mission calibration proposals along with the normal science proposals. The Gaia "solution" for close to 100 ground-based calibration proposals was an "Official GBOG stamp" to mark proposals that have been coordinated but it is difficult to draw a dividing line between essential and non-essential calibration work.

Gaia specialty: Exact angular position of the Gaia satellite for orbit determination in order to achieve the ultimate astrometry for the Gaia catalogue. This is more an engineering project than science (although many new asteroids were discovered on from these images of the Gaia satellite). Credit is to be given for the provided ground-based observations.

Gaia specific challenge due to no data rights for anyone in Gaia. All joint "early access proprietary data exchange proposals" are denied. Many ground-based survey projects are led by a PI with proprietary access that benefit of the open Gaia data while scientists working to get Gaia data public have no access to the ground-based survey data. In reality no major feelings of unfairness have occurred as many PI-led big surveys also aim, and feel the moral obligation, to make their data public before exploiting it fully in combination with Gaia data.

The Ground-Based View (Keynote 3 plus contributions and discussion**)**

Part of the challenge is that the astronomical community has access to such a large number and rich diversity of ground-based facilities. Optical-infrared ground-based telescopes with up to 40m aperture, sub-mm telescopes, radio telescopes of all sizes covering many frequencies, operate alongside space-based telescopes in all domains of the electromagnetic spectrum. In addition, many opportunities/facilities increasingly involve combined multi-messenger science, like gravitational waves, neutrinos or cosmic rays.

ESA-ESO working groups have been instrumental in kick-starting some astronomical missions and/or instruments (Euclid, HARPS at La Silla, Gaia). Different levels of coordination were identified: [1] astronomers (bottom-up identification of what is needed/desired), [2] observatories (coordinated and at times complementary capabilities, sometimes also competition/duplication; coordinated scheduling, and homogenization of archive/data standards), [3] funding agencies (e.g., with a view to funding stability for long-term projects ensured by national funding agencies), [4] facilities (different observing modes, users base, or the level of specialization on specific science drivers). As an example, ESO's role in hosting the HST European Coordinating Facility was vital to developing expertise/capabilities that would later serve the ground-based European astronomer community.

Moreover, coordination of ESO and ESA through SCIOPS conferences (attendees mainly from ops departments, not scientists) helped project planning, execution and support. Experience showed that, at times, proposed observations have to overcome notions of "entitlement/blackmailing" when it comes to coordinating (ancillary) observations. On the other hand, cooperation may not always proceed through provision of "new" data, but can also extend to archival data (see example of large data base of spectroscopic redshifts that could potentially already be used to calibrate Euclid redshift measurements). Coordination via joint proposals could be the way ahead. "Desirements" for observatory operational capabilities include flexibility, uniqueness and complementarity.

Going forward, all data needs to be in data bases in order to be of interest to/used by the community (open access leads to highest impact). This requires financial investment (that could otherwise be used to build, e.g., instruments). 3-tiered system of observatories can be considered: flagships, workhorse telescopes, archives (increasing degree of specialization if you are a flagship, or a smallish workhorse telescope). Coordination is made easier if observatories manage to build bridges between (sub-)communities – see e.g., gravitational wave source follow-up via single ENGRAVE proposal vs. fragmented, hard-to-coordinate follow-up of GRBs. If an observatory is flexible and operates multiple facilities, it is possible to think about "conditional/refined" follow-up strategies (e.g., pick telescope size based on plausible/known brightness of counterpart).

In summary: Flexibility is needed because astrophysics covers many topics and techniques, for completeness of instrumentation, and to react to interesting new events, objects and topics. Coordination requirements have to consider instrumentation programmes at different facilities, either through a large pool or through collaboration between observatories, planning between ground and space, and time allocation between observatories. For operations, inbuilt flexibility is needed as well as an open archiving and distribution of data.

AstroNet was mentioned as an example of a "counterproductive" roadmap of space missions, led by a non-representative, small fraction of the community. Nevertheless, some roadmaps can be useful, good examples exist where they have been used to build science cases. Plans for equipping ESO telescopes to become more "specialized" via the deployment of dedicated instrument suites have been discussed, in particular as regards some of the 6-10 m telescopes. This re-purposing becomes increasingly likely once you drop out of the "flagship" category. For the VLTs such changes will be difficult as long as VLTI should be continued.

Funding for new instruments vs. funding for archives vs. maintenance of existing ones was raised. Are archives not sufficiently high-profile to convince funders of their raison d'être? There is a need to set up a European Archive structure (single organization & structure). Lots of efforts going on are proceeding on a distributed basis; this does involve collaboration, sharing of good practice/code.

How do you balance funding between flagships and workhorse telescopes? The latter arguably have a more favourable "astronomers per money" performance? However, Nobel-prize winning science cases are clearly very compelling and important to attract funding. There was broad agreement that the dilemma not to "quench" 'volume'/workhorse observatories exists, and that they will continue to serve a large(r) community.

The US perspective was centered on the experience with Rubin (formerly LSST) and Roman (formerly WFIRST). In the case of Rubin, 1.2M USD was spent on a data analysis system; of order 1e+10 objects and 7e+12 "sources" are expected. Rubin had to rethink how observatory and archive is constructed. Rubin could be considered as a big data base with a few bits and pieces of hardware attached. This project opens an era of "massively parallel astrophysics" (observatory does one thing and people use data stream for a broad variety of things). It also involves an outreach component; in that it provides resources for people with a broad range of expertise to access data/track objects. Many of the transient events detected by LSST will be at faint flux levels (for LSST, an 8m telescope). Only the brightest will be accessible by small telescopes often touted as primary candidates for LSST target follow-up. This implies that we will need large facilities to participate to follow-up efforts as well. There is also a brokering/triggering/delegating problem, caused by the large number of events each night. How do you find a needle in the haystack, the few really interesting objects that "deserve" triggering more than others do? A new way of doing astronomy will be necessary: Have to ask the crazy questions, not necessarily search for answers to well-established questions. There is a need to design a data base that can handle a wide range of user-developed software/queries.

Roman is a 5-year mission, 100x FoV of HST, with a 2.4m mirror. The Roman survey depth is comparable to the Rubin ten-year survey depth. Matched depth is good for many applications, it allows to combine high-res information (Roman) with multi-wavelength (Rubin) information. Plus, Roman provides more NIR coverage for, e.g., photo-zs. Similar argument made for Euclid + Rubin, except that Euclid depth is similar to Rubin one-year survey depth. This enables contemporaneous, depth-matched multi-epoch studies.

There are currently no official plans to coordinate 6-10m telescopes worldwide. The issue is brokering when only 6 brokers are fairly organized. The second issue is scheduling, i.e., deciding which instrument should carry out the follow-up. In the US this is being looked at by NoirLab. No one has really taken ownership of this (by necessity this is left to the community, as observatories like Rubin are not to be judged based on their performance to implement this). Follow-up needs an up-front science case (and more than just generic science cases). This is better than some observatories, by default, dedicating a certain percentage of time to follow-up. Existing examples of coordination via a "dashboard" of scientists that select interesting events for follow-up, will be done by the 6 aforementioned brokers.

What about north vs. south sky coverage? The community approach to this appears to be random, based on national preferences. Should this be coordinated? Indeed, there is little coordination, but it is necessary to understand and develop a compelling science case. For statistical studies one hemisphere may be ok. ESO Council is aware of need for workhorse telescopes. Their role is recognized in the ESO portfolio to be part of the palette of offerings. ALMA is both a flagship and a people's observatory. Large programs don't get through. Time available for non-GTO teams will be small during long commissioning phase. (But GTO teams will involve large parts of community.)

It is a testimony to the good planning of Rubin that the observatory has thought about data needs, etc. from the beginning. This highlights the need to think design an entire experiment, not only an instrument. There are lessons to be learned from this also for synergistic ground + space projects. They need to be planned as "experiments" requiring a range of resources, looking beyond just the hardware.

The Exoplanet View (Keynote 4 plus contributions and discussion**)**

Exoplanet science is currently the driver for many astronomical projects. The goals of the planetary sciences are to understand processes of formation and evolution, and to search for life by characterizing the atmospheres of temperate exoplanets. Challenges: planets are far away, small, dark and close to their star, contrast ratios of 10^9 in the visible or 10^6 in IR are needed for direct detection.

This is a multi-dimensional task: there is no single technique, nor single wavelength through which these goals can be achieved in a stand-alone way. There is no single scientific field that can provide all answers on its own either. A multi-disciplinary approach is needed. Ground and space are highly complementary.

The number of transiting planets is exploding: every 39 months the number of exoplanets doubles. But small, moderately temperate planets are still rare. For planets with mass below 5 Earth masses and radii R below 1.5 Earth radii, with flux below 5 times that of Earth, we know only about 40 planets today.

The whole exoplanet story is a story of precision measurements. Masses are now based on spectrographs measuring radial velocities with approximately 10 cm/s precision, while the size measurements of exoplanets are based on light intensity measurements through photometry with around 20 ppm precision. The former is achieved with ground-based telescopes while the later corresponds to space-based missions.

The Mass-Radius diagram is a first step towards characterization. Exoplanets below 5 Earth masses follow Earth-like composition. The maximum mass of rocky planets is around 25 Earth masses, possibly indicating the maximum core mass able to accrete. TOI-178, a planetary system with at least 6 planets, was discovered by TESS, and observed later with CHEOPS, as well as from the ground with NGTS and SPECULOOS. It will be observed by JWST to characterize the planetary atmospheres. This is a good example of synergy between different instruments – ground and space – in order to better understand the dispersion in mean densities. Surveys for exoplanets (radial velocity [RV] and transits) are in the hands of consortia, who built the instrument and benefit from GTO time. Collaboration happens inside the consortia, also the negotiations (e.g., about authorship). Agencies (in Europe) have played no large role in organizing the collaborations, they are mainly facilitators. Collaboration is in the hands of the community but the RV community is very protective.

The ESA satellite project PLATO is an example of a real challenge for ground and space coordination. Ground facilities are needed in different ranges: 1-2 m telescopes (800 nights over 6 years), 4m (700 nights over 6 years), 8m (240 nights over 6 years), or ELT for Earth-like planets on long orbits. Some agreements failed for RV measurements.

Spectroscopy is the necessary next step in the characterization of exoplanets. The easiest is transit spectroscopy with JWST, ESPRESSO (for individual cases), while ARIEL will address statistics (~1000 planets). The most interesting planets must first be identified, in order to be able to follow them up with JWST, exemplifying the essential role of small telescopes. Small satellites doing transits are also needed to get good ephemerides, allowing the correct timing for targeted observations with bigger facilities. The statistical problem is the need to monitor about 200 stars to get one Earth-like planet (not very efficient, 0.5% probability of transit).

Direct imaging is necessary to probe Earth-like planets, but current instrumentation still lacks the necessary precision. The future is ELT with first light in 2027 (METIS & HARMONI are first-light instruments). But the characterization of more than 10 temperate planets must be achievable within a large mission. NASA´s decadal survey published in 2021 also identified a technology maturation program as a must for new telescope looking for life (6m telescope). Nevertheless, agencies plan their space- or ground-based infrastructure independently. ESA and NASA share very similar science goals and they have to face the alternatives of collaboration vs. competition, or dropping the goal entirely. What kind of collaboration could be envisioned (50-50 or 20-80)?

Large research infrastructures are being planned/built without developing the necessary supporting framework. The system does not reward the personnel involved, especially the junior ones. Segmented mirrors represented a breakthrough for telescope construction and allowed to go from 5 m diameter to 39m. As a result, the cost of construction and launch has decreased dramatically: this changes the game, also because it enables new technology.

The ultimate goal is the search for life, but how do you find something you don't know? Where to look for it and how? In situ, or via biosignatures in the spectrum? How reliable would a detection need to be? Facilities for this goal are clearly beyond the capabilities of one single agency: a global effort is probably needed, and a lot of technology still has to be developed. Exoplanets and the search for life serve as a key science case for a number of future facilities, and catalyze discussions on how to work together given the respective constraints. Scientists from all around the world should work on signature scientific challenges like these, and whichever agency is ready should start leading that effort.

100'000 exoplanets will be known in the next decades, and around 5% will be Jupiter-like studied with Gaia. Regarding privately funded projects, the special case of Starshot was mentioned, but it involves difficult technology that is expensive and long-term development. The several ongoing projects for transit monitoring can be useful as long as agreements on data release can be negotiated. One example that was pointed out was a Cubesat, that passed the proof, and cost 6 million Euros. Coordinating that kind of effort is hard, esp. if – as in this case – they are developed by small agencies.

Exoplanet science needs dedicated missions for better statistics. Ariel data will be released immediately after processing, and only 5% of the data will be released after one year (the more challenging cases). 1000 exoplanets targeted is better than the ~10 we have now regarding information on their atmospheres. Ariel will study molecular composition, clouds. Ionic species will be studied from the ground. Data challenges are to train the community to use the data, to have catalogues available through an interactive way and open-source tools (VO!). An open platform is needed to monitor the ephemerides of Ariel with hundreds of active participants. Discoveries coming from next 10 years facilities, and the things we will learn with the facilities themselves, will be critical to guide future endeavors. Synergies with ground-based facilities still need to be identified. For habitable zone science JWST is certainly ideally suited. In addition, it will serve for calibration.

In summary, the discovery and characterization of exoplanets involves different techniques and relies on an ecosystem of small and large telescopes, from ground and space. The community is not "forced" to unite behind single large experiments. There will be more planets than scientists working on this subject, as opposed to cosmologists with "only one universe". The next decade will the decade of synergy between space and ground-based facilities.

Structured discussions

The key point addressed at this ISSI Forum is how to improve the coordination of ground and space observations in the future, for the benefit of science and society. Coordination in some cases is not only beneficial, it is also essential, e.g., for space VLBI, a model for successful cooperation and coordination for future ground and space efforts, with many players involved.

What specifically can be learned from ongoing research? Build collaboration from the beginning, in a global way. It is essential to engage, at early stages, with appropriate parties in different countries, being aware of cultural/structural differences. Plan now for what will become mature in 20-30 years. Timescales and timing are always a challenge (not least to build enthusiasm among young scientists for what they will be exploiting only as senior scientists). Be careful to define "requirements". They can come back to haunt you if they are not easy to fulfill; especially if they become part of the review process. This has implications for how coordination/connections are set up/communicated.

Lessons from Gaia serve as an example of a project that was conceived as "open data" from the outset. It involved no hardware contribution from member states, but huge in-kind efforts instead. The DPAC team was exemplary in being unselfish and working in a constructive spirit. Open data policy was inserted low-key, almost unnoticed early on (not as a particularly conscious decision), later there was some push-back, but it was impossible to revoke at that point. This open data policy of Gaia with no proprietary period whatsoever is received enthusiastically by the international community, it is an ideal model and provides a very good aspiration. But at the bottom of the food chain, we receive the question from funders what we get in return (e.g., Prodex in Switzerland). Answer "For public, science to be done on first come, first served basis" is not popular. This is a dilemma, but science-wise open data is best. We need compromises, ensuring that money to build instrument actually flows. Otherwise, nobody gets any data.

A compromise that consists of making the proprietary period quite short has been adopted in some cases. Ultimately, agencies need to be able to showcase successes to political decision makers. Examples are the SDSS and TESS teams: Define „builders" or "architects" who can join all papers, this seems to work well. However, whether this works may depend on the funding landscape, e.g., funding for instrument building and exploitation can be completely separate. A paradigm shift is necessary not only at funding agencies, but also among scientists, the scientific system is built on rewards/visibility.

Funders need to be made to understand that support is not only necessary for instrument building, but also exploitation. In small countries otherwise there may be fear that one may subsidize science done in other, bigger countries. Otherwise, the risk is that industrial return will always be the main argument/sticking point for obtaining funding. Proprietary time is an attempt to solve the problem by building fences. An excellent example is NASA/HST: successful observing proposals come with additional support for postdocs in USA.

In many ways we are faced with a Catch 22 problem. GTOs should only be an initial phase, then PIs themselves should strive to open data (e.g., for INTEGRAL this led to better return for PIs). This is a very effective approach. NASA for some missions is already now setting aside money for PIs and exploitation. It is important for many member states that hardware investments are recognized by GTO. Taking ALMA as an example: The fact that the observatory is still predominantly carrying out short-duration programmes is due to no GTO programmes being scheduled at beginning. Spitzer was pioneering in their legacy surveys which were public immediately. Teams simply got money to develop/exploit their data.

The changes brought about by the Big Data era might make for a more level playing field. Some of the costs are outsourced as one will apply for both observing and CPU time. FERMI-LAT is another example of why in-depth knowledge matters. Having data public did not cost anybody anything, apart from some poor papers. This is a self-correcting process. Ultimately, results were only accepted/solidified once robustly written papers by FERMI-LAT team were published. Herschel used GTO very effectively, with surveys that would have been hard to route through PI process. XMM is a less good example, and it was intriguing to hear the assertion that ALMA is stuck in short-project mode due to omission of GTO phase. This would warrant more investigation.

The statement that US support for exploitation following accepted HST proposals represents a big advantage is a red herring. Europe has an over-proportional return on investment on HST by various metrics.

Observatories need to think strategically whether large programs provide good investment. Open data is best: "If you are scooped that is the best sign that your data was worth acquiring." New member countries often come to ESO after a few years complaining that they aren't getting return on investment. This is often the case because they have not started early on to build/support their communities in a proper and sustainable way. Large programs and acceptance or permissible time budget for large projects can be lobbied for. The community could come together to gather momentum for this.

Astronomy in general may be partly moving towards survey science, maybe giving future young astronomers more data access than was the case so far. „Large program" (LP) is not necessarily synonymous with high impact, but 45% of normal PI observations do not get published (!). For LP there is statistically more guaranteed return. Teams have a vested interest to get things done. Those collective mechanisms start to work and benefit from a better "internal" organization. LP also benefit the community as they are required to add reduced data to the archive.

An IAU "neutral" working group for the coordination of ground + space observations involved observatory directors and they appreciated the opportunity to interact. It is also important for developing countries to build a technical and scientific skills base, preparing for their own top-level facilities. This implies that the ISSI Forum reaches new communities. One could do more: at the moment all is organized/coordinated on a voluntary basis, and the cadence of meetings could be increased. Good topics for future meetings could be far-IR and/or mm/cm-synergies. Sessions are open to everybody. Both scientists and observatory staff participate. There is a healthy difference between coordination among (i) scientists (e.g., IAU WG or ISSI Forum) and (ii) agencies. The latter need to go through different channels; mixing both has rarely worked. But communication between the two is essential, to make sure everyone is on the same page, re. what is realistic (e.g., based on the likely funding available).

From the standpoint of the US, tensions between different agencies are often an issue. "Talking to the Americans" is not a valid concept – nor is "talking to Europeans". There is heterogeneity. This really is entering science diplomacy. But there are clearly defined channels of communication in such cases which, if not followed, will result in even bigger problems. This is at the core of the issue of achieving collaboration. How static is this "standard practice" approach? Clear rules are useful, and essential for acceptance of the outcome of processes, see the ESA Voyage2050 report. This has resulted in recommendations for 3 ESA flagship missions. Medium/fast missions can still be decided. Ground-based science could provide driver for some. ESA is appointing JAXA, NASA, etc., people to advisory committees in addition to European scientists to ensure that these flagship missions serve the largest possible community.

Concerning how to address technological difficulties for future large space missions and ground telescopes, the approach of particle physics could be followed, but there are some doubts about it. As long as we have not set a goal, nothing happens. The lack of seriousness in developing the needed technology is felt. There is a perception in astronomy that the community seems to be in love with one technique and does not listen to the engineers. The way ahead could be to develop programs to facilitate the technology advance. This approach is adopted in ground-based astronomy for high precision radial velocities leading to the orbital study of exoplanets. The search for life requires new imaging capabilities and larger telescopes. New technology developments for mirror technology will be needed for this next step. The necessity of achieving a genuine breakthrough in these areas was widely recognized. However, there is not even a "back of the envelope idea" about how to achieve it.

Until there is no collaboration, there is no advance. No agency can be the single partner. ESA and ESO have learnt to cooperate with ALMA, without direct involvement, and there is no reason why not doing it with others. There is no other solution than collaboration, without killing alternative unexpected ways. If you don't push the system, you don't get anything.

Conclusions

Exoplanet research and cosmology and extragalactic astrophysics clearly both need space and ground-based facilities, working in synergy, but other areas of astronomy also benefit from such synergies. For Galactic astronomy too such synergies are beneficial, e.g., between Gaia and Plato in the determination of the ages of stars or galactic dynamics. In addition, ground measurements are not limited to telescopes across the electromagnetic spectrum. Multi-messenger astronomy relies on the detection of gravitational waves or high-energy particles from the ground. The ultimate aim is to better understand the physics of the Universe.

Most problems in the cooperation and coordination of space and ground astronomy have been identified. Also, some possible solutions and their intrinsic challenges. What to do now? What can we do to open the way for international cooperation? How to extend these discussions to the community? How to keep these discussion alive and track progress? In principle, ISSI could organize a follow-up Forum or even a working group of 10-20 people, that could meet for a week per year. Nevertheless, there was a consensus that it would be good to include the "whole world", so the discussions have to be extended beyond a reduced group of experts. IAU and COSPAR were identified as the right environments for further reflection on the open issues. This Forum will certainly have influence on the program of the IAU GA 2022 in Busan but also at the COSPAR GA 2022 in Athens. ISSI is hesitant to duplicate work that is being done elsewhere but could follow this up, making sure that there is good global connection between scientists and agencies. Solutions can be found only together and have to be realistic, feasible and affordable.

At this Forum the synergies and challenges of ground and space astronomy have been identified but they cannot be complete without enlarging the involvement to scientists and agencies. Furthermore, it is important that somebody "neutral" is looking at it. Thus, we have to define a series of workshops to follow-up the discussions. In particular the possibility of a small working group, involving a few key people, to be later organized at ISSI, but not earlier than after 2 years, was considered. This group could review the progress/synergy between ground and space, and might apply some pressure to the groups involved. We are afraid that without further action the response to the identified challenges will be put into the drawer, while the problems have not disappeared.

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