

Article

Gender Balance in Mars Exploration: Lessons Learned from the Mars Science Laboratory

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Abstract: There is, recently, a global concern about the gender gap in Science, Technology, Engineering, and Mathematics (STEM) areas, starting from education role models, student applications, through the academic, industrial and management career progression. Given the high visibility and popularity of all subjects related to space exploration, female participation in this field may be used to change the existing stereotypes and provide role models to the younger generations, thus having a positive influence on education while also demonstrating to other organizations how to promote diversity in the working environment. Previous studies on spacecraft science teams, considering only principal and co-Investigators, PIs and co-investigators (CoIs), respectively, show that the percentage of women in the role of investigators has remained flat at 15.8% since 2000. The NASA Mars Science Laboratory (MSL) mission is taken here as an example to perform a statistical analysis of the gender profile for the period 2004–2018. The results are compared with: (1) data from the US National Science Foundation (NSF) about gender distribution in STEM postdoctoral profiles and faculty members; (2) the trend of planetary exploration team profiles; (3) research and innovation statistics in Europe; (4) proposals of the EU FP6 funding program; and (5) the percentage of female researchers from the Elsevier status report. This analysis shows that the process of continually holding open calls for Participating Scientists based on individual merit and the application of a flat working structure have allowed gender balance within the MSL team to improve naturally while maximizing individual and team performance. Women represent approximately 30.6% of the team, in agreement with the current percentage of female planetary exploration researchers and senior faculty members in academia. Interestingly, the percentage of female-led articles has been above the MSL women percentage trend. While the percentage of women in planetary science appears to be increasing, their role on the proposing teams is still low. As in other STEM fields, attention should be paid to secure the adequate promotion of younger generations to achieve the United Nation's Sustainable Development Goal 5 of achieving gender equality and empowering all women and girls by 2030.

Keywords: solar system exploration; gender balance; mars science laboratory; sustainable goals

1. Introduction

The 2030 Agenda for Sustainable Development adopted by the United Nations (UN) General Assembly in September 2015 promotes a new global approach to address the environmental, economic and social concerns that our world is facing today [1]. The Agenda includes 17 Sustainable Development Goals (SDGs), including SDG 4 on education and SDG 5 on gender equality. The recent report of the United Nations Educational, Scientific and Cultural Organization (UNESCO), *Cracking the code: Girls' and women's education in Science, Technology, Engineering, and Mathematics (STEM)* [2], has demonstrated that gender differences in STEM education participation are already visible in early

childhood and become more visible in advanced studies at secondary level. Only 35% of (STEM) students in higher education globally are women. Multiple factors seem to be responsible for these biases, but one of the solutions proposed to motivate female students to follow STEM training is to provide role models and inter-generational cooperation through mentorship opportunities. The UNESCO report has concluded that “Gender stereotypes portrayed in the media are internalised by children and adults and affect the way they see themselves and others. Media can perpetuate or challenge gender stereotypes about STEM abilities and careers” [2]. Given that space exploration is a field that is deeply rooted in multiple disciplines of STEM and it has high visibility in the media, female participation in this field may be used to change the existing stereotypes and provide role models to the younger generations, thus having a positive influence on education. This work wants also to showcase the female participation in one international and long-term, space exploration mission to explore what methods may be used to facilitate the incorporation of women in STEM-related organizations.

Unfortunately, once students join these subjects, the biases are maintained at university level and beyond. The systematic lack of recruitment, promotion, and retention of women in STEM is a concern, and the existing cultural, structural, institutional, and societal barriers that hinder gender balance are being extensively investigated. There is a need to analyse the existing difficulties with data-driven approaches to increase awareness and propose solutions, and to reflect about what best practices may be used to promote equality [3,4].

Many disciplines are attempting to close the gender gap in their communities, and space science is one of them. More females are engaged in the field of space exploration now than 50 years ago; however, there is still significant room for improvement. As in other STEM disciplines there is a notorious lack of women in leadership roles in space research [5]. Attention should be paid to secure adequate training and then promotion of the younger female generations to facilitate gender equality in this field. The United Nation’s Sustainable Development Goal 5 aims at achieving gender equality by 2030. Research and academic organizations, and policy makers, should play a driving role to facilitate this goal providing examples of good practices and demonstrating how competitiveness is favoured when gender equality is reached. This is the starting point of this work, the assumption that when the outstanding excellence of the product is pursued, gender biases tend to be neutralised. This work takes one specific example of a space mission to illustrate the recent trend changes and to analyse some of the existing tools that may be used to break inherited barriers in this and other fields.

When the Mars exploration started in the year 1975 and the Viking probes were sent to Mars, there were no women among the 78 members of the science team [6–9]. After 1976, there have been other successful missions to Mars, such as the rover Pathfinder [10], the Mars Exploration Rovers (MER) [11–13], and the Phoenix Lander [14]. Since 1975, there has been a significant increase in the ambition, duration and complexity of space missions, with more international cooperation, and a larger number of people and institutions involved on its organization and execution. Many of the mission tasks are now distributed at different geographical locations and time zones. The missions require large science and engineering teams participating in their long-term operation and exploitation. Most of these activities are now done through internet-based platforms and there is a certain level of rotation in science teams which is considered as positive. Little attention has been paid so far to the influence that these new science management structures have had on gender biases. Here we consider the NASA’s Mars Science Laboratory (MSL) rover Curiosity as a study case, to evaluate what management lessons can be taken from this current mission. Some previous information is required to understand the peculiarities of this challenging Mars exploration mission.

The MSL Curiosity rover is currently exploring the Gale Crater on Mars [15,16] on a quest to understand Mars as a potential habitat for microbial life in Mars’ ancient past [17–19]. Curiosity is a long-duration mission (it started in 2004 with an “announcement of opportunity” and has been in operation on Mars since 2012), with 10 instruments on board that require continuous communication with the rover and the coordination of a science team of more than 480 scientific and technical staff located at different institutions and in different time zones worldwide. This mission is particularly

international, with instrument payloads from Canada, Spain, Russia, France, Germany, and Finland. Working on Mars has some additional peculiarities. A challenging one is the operation of a spacecraft that it is so far away that the communication delay with orbiters can be between 4 and 24 min. Additionally, this signal has to be sent to the surface, which can only occur once or twice a day during the satellite orbit pass. To cope with this, the operation of such a rover is executed within a 24 h latency, which is the time between receiving the data from the previous day, analysing and discussing, planning and transferring the instructions for execution back to the rover on Mars. In practice, this requires a tremendous effort of integration and close communication between the backroom scientists and the spacecraft engineers who participate in the operation of such a science-driven mission [18–20]. Furthermore, the operation shifts have to be rescheduled from time to time because of the difference in the duration of a day on Mars (a Martian day is approximately 41 min longer than a day on Earth). The planning of activities must also incorporate external factors such as the position of the orbiters that act as a relay of information between the Earth and Mars and the position of Earth, Mars and the Sun during the solar conjunction period. In summary, a large human effort is needed in order for the mission to be successful.

The NASA proposal call for instrument contributions was released in 2004, and the official agreements concerning the mission were established then with the leading principal investigators (PIs) and proposing institutions that made a commitment to deliver each one of the selected instruments. Most payloads were from USA, but some were contributions from other countries, such as REMS, from Spain [21]. During the long development phase of the mission, the MSL Science Office management consisted of the Project Scientist and two Deputy Project Scientists (one of them a female). Significant responsibilities were distributed among them, without any one person dominating the effort [17]. When the MSL Science Team was officially formed at the time of landing, it consisted of the instrument PIs and instrument co-investigators (CoIs) who are part of the instrument proposing and development team plus instrument collaborators, one Project Scientist (Proj. S.), two Deputy Proj. S., one Program Scientist (Prog. S.), and one Deputy Prog. S., as well as the Investigation Scientists that had a liaison role during the MSL payload development. This science team was complemented with collaborators. Collaborators may be students, postdoctoral students, or technical staff collocated with and working with team members. This long-term space mission is of particular interest because it includes a non-formal educational program, where young researchers are incorporated regularly (graduate students, PhD and postdoctoral students) and are mentored or cooperate with more experienced scientists.

Right before the MSL launch in November 2011, the first call for Participating Scientists (PSs) was opened. These PS calls have been periodic since then, allowing new PSs to be incorporated. In parallel, students that are supervised by science team members can also join (and leave) the team while their research is associated with MSL. The MSL Science Team consisted of 483 members who all must adhere to a Rules of the Road (RoR) document governing open team interactions, data sharing, and publications, as seen in the Supplementary Materials of the first MSL publication [17]. Most science team members share this work with other duties, and therefore, a smooth coordination is even more critical. This team also ensures that the instruments are operational and performing well, providing assurance that this huge technological challenge is successful in paving the way for future exploration efforts. Most importantly, this team releases, for open access to the general public and to the science community, the full scientific data sets and contextual information to the Planetary Data System (PDS) [22] (for instance, as of today, more than 500,000 images have been uploaded to the PDS) and produces original research in peer-reviewed journals to facilitate their interpretation and expand the state-of-the-art of knowledge.

The MSL mission and its rover, Curiosity, is one example of a successful, long-term, and unique space exploration mission where scientific and technological excellence is pursued. An analysis of this case is presented here in an effort to propose solutions to improve the representation, experience, and promotion of women in space exploration and, in particular, in STEM subjects [23].

2. Materials and Methods

The gender balance of the MSL team has been analysed with the information available according to the RoR, as found in the Supplementary Materials of the first MSL publication [17], and with the MSL science team list that all participating team members have access to and that is also named “MSL author” in some team publications. This has been compared with data from the following sources: (1) the US National Science Foundation (NSF) profiles about gender distribution in STEM, and faculty members [24,25]; (2) the trends of other space exploration missions [5]; (3) recent statistics from Europe for research and innovation [26]; (4) proposals of the EU FP6 funding program [27]; and (5) the percentage of female researchers in these subjects in Canada, the EU and the USA [28]. Finally, the key working principles of the MSL teams are discussed to interpret the positive trends. The MSL Science Team members were competitively selected or appointed by NASA to conduct the MSL science investigations. This study does not consider either the thousands of engineers at the NASA Jet Propulsion Laboratory (JPL) and its partners and subcontractors that designed, assembled, tested, and operated the various spacecraft elements of the MSL mission through landing or the engineers that currently operate the rover. This study finishes in 2018.

3. Results

The gender profile distribution and its evolution through the years is summarized in Table 1. In 2012, when the rover landed on Mars, the gender distribution was of 0% among PIs and 12.1% when CoIs were considered. The PI and CoI teams are those that ensure that an instrument is delivered and fulfils the requirements to achieve its goals. These teams are also generally responsible for searching for funding for development and scientific exploitation through competitive calls and with the national space funding agencies. The female percentage rises to 14.6% when the PSs are included and to 20.5% when associated PSs are considered. If the total MSL team is subdivided into science team members and science team collaborators, then the science team list has 22% women, whereas the total MSL team in 2012 had 27.1%.

Table 1. Female participation over time in the Mars Science Laboratory (MSL) Science Operations Team and in the core team of Principal Investigators (PIs), Deputy Investigators and Co-Investigators (CoIs), MSL Project and Program Scientists (Proj. and Prog. S).

Group Category	Year	Total	Female	% Women
PIs, MSL Proj. and Prog. S	2004–2012	11	0	0
Deputy (PIs, MSL Proj. and Prog. S)	2004–2012	8	4	50
Investigation Scientists	2004–2012	7	1	14.2
PIs, CoIs	2012	124	15	12.1
PIs, CoIs, MSL Proj. and Prog. S, PS	2012	158	23	14.6
PIs, CoIs, MSL Proj. and Prog. S, PS and A-PS	2012	205	42	20.5
MSL Science Team	2012	150	22	14.7
MSL Science Team and collaborators	2012	407	110	27.1
MSL Science Team	2018	145	28	19.3
MSL Science Ops. Team	2018	483	148	30.6

Since 2012, MSL has had a continuous flux of people joining and leaving the team through the PS calls. In addition, young students who are associated with science team members come and leave the team as part of their training. This allows the involvement of new team members with renewed diversity, and as a result, the gender balance distribution is dynamic over time. By the end of 2018, 293 of the 483 involved members on the science and operation team were on the team when the rover landed, and 190 people had left the team during the same time period. By 2018, of the total team of 483 that make the science operation team of MSL, 141 were technical staff and 145 were PIs and CoIs.

The remaining 197 consisted of 101 research associates, 31 postdocs and 65 students, all of whom were engaged in a research-focused activity. By this moment, women represented approximately 30.6% of the total science and operations team.

The gender profile distribution and its evolution through the years is shown in Figure 1. This distribution has to be analysed in a broader context. First, regarding the observed US trend for women in planetary scientists from 1987–2013 [5] (although this study is more focused on the statistics of the astronomy community), this trend is extrapolated backward and forward for contextual comparison; second, a comparison is made with the existing reservoir of female researchers for the specific MSL area of research (geology, physics, atmospheric science, chemistry, microbiology, engineering, etc.). For this purpose, I analysed the data of the STEM area for multiple years from the National Science Foundation [24] and compare it, when available, with the statistics for the merged field of a subset that is referred to here as Engineering, Physics and Geology (EPG), consisting of the natural pool of specialists for such a mission on Mars. I have also included for contextual comparison the women as a percentage of science and engineering doctorate holders employed in academia by position for selected years in the period of 1973–2015 as postdocs and senior faculty members [25]. In addition, to include an international perspective, I have included the proportion of female researchers (among named and gendered author profiles) for three of the participating nation blocks, namely, the US, the EU and Canada (in this report there were no available data for Russia), as evaluated by the international publisher Elsevier for the periods of 1996–2000 vs. 2011–2015 on the subject areas that have been categorized and that would apply to this mission: engineering, physics and astronomy, chemistry and Earth and planetary sciences [27]. The results are shown in Figure 1a.

The evolution of the science team publications, and the female-led articles, as they appear in the list of key MSL science papers of the PDS [22] is summarized in Figure 1b. The number of articles shows a positive average increase of 9.4% per year. The percentage of female-led articles is also included (an average of 30% of the articles) and is always above the MSL women percentage trend. It is worth noting, however, that the first authors are often not the project leaders, but the junior scientists who take first-hand responsibilities on the analysis and discussions. Depending on the field, project leaders may be placed in second or last position but being first author of articles gives visibility to young academic researchers and it is the first step to apply for funding and promotions. The increase in the total number of publications appears not only as more maturity is reached in the interpretation of the observations but also as more science team members join the mission, diversity is naturally incorporated, and more institutions have first-hand access to these observations.

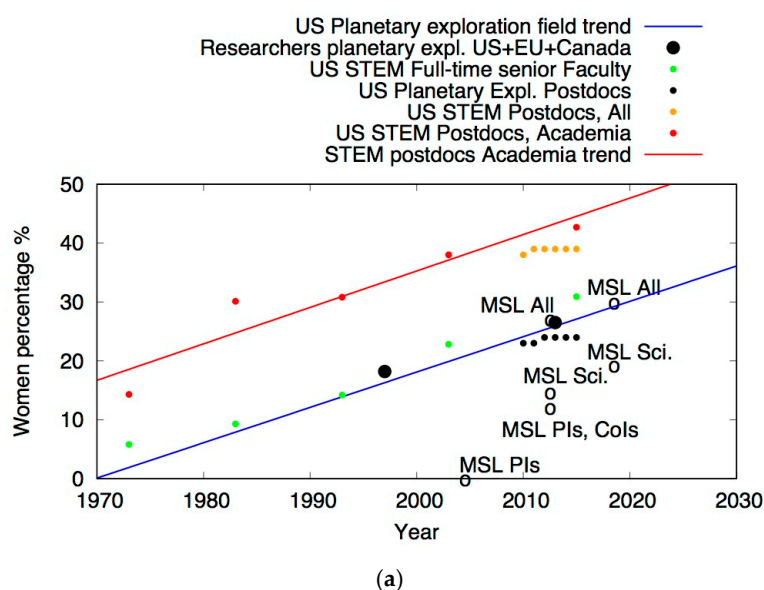


Figure 1. Cont.

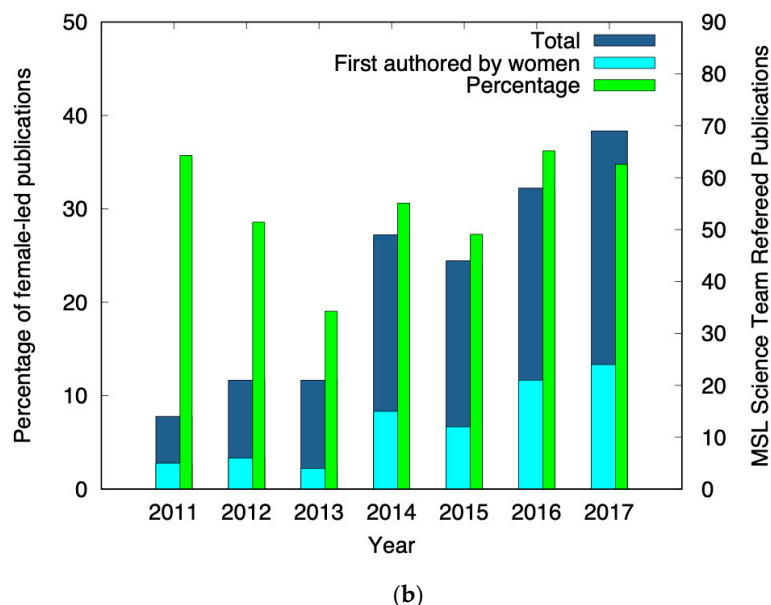


Figure 1. Time evolution of (a) percentage of women in the MSL team and space exploration and in postdoctoral, research and faculty positions of the field and STEM. (b) Refereed publications of the MSL Science Team and percentage of female-led articles. The references ascribed to 2011 were published in the years of development between 2008 and 2011. A total of 34.8% of the papers published in the 2017 have been led by women.

4. Discussion

There is clear gender gap in the constitution of the leadership of the initial proposing team, in agreement with a previous study on spacecraft science teams, including only PIs and cols, which shows that since 2000, the average percentage of women has remained flat at 15.8% [5]. This also applies to MSL, where women constitute 12.1%. According to Figure 1, when the first MSL team was formed, females were underrepresented with respect to the female ratios that were common in that research and development area. However, this has been changed, at least in non-decision-making positions, with the incorporation of more team members. The analysis shown above illustrates that by 2018 women represented approximately 30.6% of the MSL team. This percentage is in line with the female ratio of planetary exploration researchers [5] and is also aligned with full-time STEM senior faculty members in academia in the US or researchers in the field in the US, Canada and the EU, which can be considered as its counterpart for comparing state-of-the-art specialization and responsibility roles in research and development activities.

The RoR methodology has significantly influenced the success of the project by encouraging opportunities for interdisciplinary results and discoveries and by enabling individual creativity and initiative, allowing all members of the project to benefit appropriately from the scientific successes of the MSL, as shown in the Supplementary Materials of the first MSL team paper [17]. In other words, a key point of this philosophy is that it recognizes that the achievement of the overall goals of the MSL requires integration of a wide range of geological, chemical, and physical observations. Furthermore, the best chance for achieving these objectives comes from merging the group into a single, interacting team with a flat structure, where scientists can coordinate in subgroups according to their interests rather than establishing a more traditional and opaque pyramidal structure of leadership and reporting. The working tools are very transversal, transparent and flat, all team members have remote access to common information platforms, and some of the operating roles are assigned in rotating turns.

According to this analysis, and, if this trend follows, it may reach the 50% limit by the year 2024. However, this is only a first step, as what tends to happen in STEM, and every other male-dominated discipline, is that gender parity stops at this level, and it does not permeate into the senior levels.

Attention should be paid to secure adequate promotion of the younger generations such that the United Nation's Sustainable Development Goal 5, achieving gender equality and empowering all women and girls by 2030, is met in this field [1]. By the early 2020s, we expect to reach more than 30% of EPG postdoctoral positions. Therefore, a similar pool should be available for Mars and space exploration. For comparison, the research and innovation scene in Europe among PhD graduates, researchers and academic decision makers is also making some progress toward gender equality within the pool of higher-education graduates [26]. In the year 2012, women made up 47% of PhD graduates in the EU. In Europe, the number of women among employed scientists and engineers grew by an average of 11.1% per year between 2008 and 2011 [26]. According to the European Union Figures on Research and Innovation, in 2011, women in the EU accounted for 33% of researchers. In summary, the gender balance trends for STEM research and innovation professionals are improving, and the ratios are specifically healthy for highly specialized PhD, postdoctoral and doctoral profiles, both in the US and the EU. However, special effort should be made to guarantee that this balance is also transferred to decision-making roles.

While the percentage of women in planetary science and STEM academic roles appears to be increasing, their role on the proposing science teams for space exploration is still low. It is known that in the research and innovation field, women are increasingly under-represented in regard to career advancement and participation in decision making [26]. For instance, in Europe, in 2013, women made up only 21% of the top-level researchers (grade A), showing very limited progress compared with 2010 (20%) [26]. In particular, in the field of science and engineering, women represented only 13% of grade A staff in 2013, and these biases are also transferred to new funded projects. For instance, an analysis of the Sixth Framework Programme of the European Community for research, technological development and demonstration activities (2002–2006) [27], which is the period when the MSL instruments were proposed, shows that only 11% of the scientific contact partners in submitted proposals were women [27]. This is comparable with the 12.1% female participation rate found on the PI+CoI proposing team. It is clear that further actions should be implemented to compensate for these inequalities in decision-making and leading positions.

Poor career progression and low representation of senior women leaders is universally acknowledged in STEM. This may be due to a combination of factors that are difficult to fight such as lack of recognition of achievements and contributions, lack of support for proposals, fewer promotions and visibility, and exclusion of women from decision-making groups, fraternities and networking. Due to their motherhood commitments and family involvement, women can also find it more difficult to travel to conferences and engage in fieldwork, workshops, training, etc. As a result, female careers take a longer time to lift off, and for positions of equal responsibility, this may lead to an additional bias caused by age discrimination and loss of opportunity. The purpose of this work is to demonstrate in which form can gender balance be promoted within a decade, in early career positions, by selecting competitively and allowing flexibility in time dedication and a flat structure. However, this effort is lost if trained female scientists have to quit as they career progresses, leaving the glass ceiling untouched.

In summary, flexibility of the working process is also a key factor in the picture of gender balance and, of course, for the recognition based on work and the avoidance of formal inherited barriers (i.e., institutional and societal mindsets, which promote the stereotypical assignment of management and leadership positions to males, resulting in an over-representation of males in these positions and an absence of female role models). Next, I enumerate some key project management tools of the MSL science operations project that may be transferred to other working environments, which would not only help the system to pursue excellence, but also avoid biases in the opportunities available for women:

1. Incorporation to the team is based on capabilities, knowledge, dedication and production;
2. The MSL science-operation system works in a concurrent way with natural screening and validation internal procedures that are accepted by all the participants. Coordination roles are

shifted from time to time. Decisions are not centralized on individuals; instead, the decisions are open and exposed to feedback from the team;

3. The recruitment of new participating scientists is dynamic and focused on the transfer of knowledge (i.e., non-formal education is naturally incorporated in the program): more experienced workers collaborate with younger people, and thus, the mentoring experience is positively evaluated, which helps to avoid age discrimination as well;
4. There are external evaluators of the products of the work: referees from external peer-review publications, funding agencies, panels and other scientists, supporting institutions, etc., who evaluate every product individually based on its quality. The performance of individuals over time is also evaluated independently (for instance, by their institutions and funding calls), and the mission is evaluated as a whole;
5. The project's equal opportunity methodology also supports individual visibility and progression in the field of research based on capability.

As for compatibility of work with personal life commitments, the following aspects are considered:

6. The working procedure is mostly internet based, allowing for flexibility;
7. Long-time dedication is continuous but flexible, and it does not require rigid commitments that cannot be shifted temporarily to someone with similar talents in case of personal (or professional) interferences.

From MSL operation we have learned that when a challenging task requires the added effort of multiple, top-quality talents, these need to be selected without biases, as any discrimination would imply a loss of potential talents. This selection approach, based exclusively on excellence, contributes to promoting gender diversity. Another key factor is flexibility of the working process, for instance space mission operations, are nowadays implemented online, allowing for the cooperation of people in multiple time zones, with varying schedules and roles. The main lesson learned from MSL operation is that flat competitive, flexible, structures give opportunities for women to rise to the level where this system is implemented, but this should be reinforced to allow women to get through the next ranks. This may be applicable in other fields now that blended work (a combination of remote and physically present work) is becoming a universal need.

Research and academic organizations should be the promoters of change to reach gender equality. Space exploration and academia need to continue the effort of breaking down existing barriers, especially regarding leadership and decision-making roles. Women are more likely than men to have a non-linear career path and are more likely to leave the academic track because of personal factors [29]. It is also desirable to encourage female research students to make an adapted career plan and pursue their future aspirations. The calls for PSs and the incorporation of collaborating roles with recognition and visibility tend to improve diversity as well and help these long-term missions to be aligned with the state-of-the-art in diversity and knowledge.

Working areas that stand out where excellence is truly pursued and that would, therefore, be expected to be highly competitive environments may be precisely the areas where gender imbalance could be extinguished naturally. The structural barriers discussed in the previous paragraphs disadvantage women, but with policies in place to shift those barriers, those women that have demonstrated individual capabilities, knowledge and an ability to produce, will be better profiled and will contribute to the success of the area under consideration, and eventually get to decision-making positions.

The number of female students enrolled STEM have been decreasing in the last twenty years, while the number of women resigning from technological job positions remains unacceptably high. New multi-factor approaches are being suggested to fight this trend, such as promoting interaction with professional women working in STEM environments and increasing the visibility of female role models [30]. The MSL science mission operation, with its flat and rotating working structure, is a practical case where some of these factors are already in place. Given the popularity of space exploration an adequate representation of female scientists and engineers in this field at all levels,

from initial educational and training programs to managing decisions, this field could be used to illustrate to the public how gender balance is achievable even in this very specialized, competitive, subject. Furthermore, by setting role models, this can awake the interest of girls in STEM disciplines from childhood and, therefore, contribute positively to the fourth (quality education) 2030 sustainable development goals [1].

As this work shows, more female authors are engaged in the field of space exploration now than 50 years ago; however, there is still significant room for improvement. The easiest way to reduce the gender gap is to give access to information, focus on excellence and to periodically conduct a self-evaluation to confirm and reinforce positive trends. Building on and enforcing these team philosophies requires initiative from the top level of leadership. The leadership of the MSL Project at NASA and at JPL have been actively promoting the ideas of collaboration, open sharing of results, etc., for the beginning of this project, and the RoR agreement and the structure behind it is just an example of this effort, which is worthy of acknowledgement. Other leaders need to be encouraged to do this as well.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/24/10658/s1>, Table S1: Female postdoctoral appointees in science, engineering and health (ALL) in all institutions (ALL) or in Academic institutions (Uni), in postdoctoral appointees in EPG (Engineering, Earth, atmospheric, and ocean sciences and Physical sciences) and Women as a percentage of science and engineering doctorate holders employed in academia, by position: Selected years, 1973–2015, Table S2: Proportion and number of researchers by gender within the EU, the US and Canada (among named and gendered author profiles) for each comparator and subject area, 1996–2000 vs. 2011–2015, Table S3: Women as a percentage of Science and Engineering doctorate holders employed in academia, by position: Selected years, Table S4: MSL refereed publications per year and female-led papers per year. If the gender of the first author is not indicated in articles, it was inferred from their professional web pages (where they existed) and the gender of their first name.

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