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Supplementary information

Estimate of the carbon footprint of astronomical research infrastructures

In the format provided by the authors and unedited

Supplementary Information

1 Activity data

1.1 Space missions

We gathered full mission cost and payload launch mass estimates for all selected missions from the internet. The results of this exercise are summarised in Supplementary Table 1. Payload launch mass estimates are straightforward to find on the Wikipedia pages of the corresponding space mission, from which we also gathered the launch and mission end dates. Reliable full mission cost estimates are significantly more difficult to compile, as mission-related documentation is voluminous, and press articles rarely include cost breakdowns. Our mass-based estimates are therefore more homogenous, but they do not account for the complexity of a space mission that also drives its final cost and eventually the carbon footprint. Likewise, they do not reflect differences in mission duration that may lead to differences in carbon footprints for the operations phase. In general, the full mission cost includes the cost of in-kind contributions to the satellite payload, yet there may be exceptions where these costs are not included. We did not explicitly account for the additional costs of mission extensions. We found that for some cases mission extensions were included in the quoted costs, in particular for all of NASA's planetary missions where annual budgets are provided by [3]. In other cases, the extensions were not included, and in a few cases, the construction cost value quotes we found were suspiciously low.

1.2 Ground-based observatories

Estimating the carbon footprint for ground-based observatories is more difficult than for space missions, since many ground-based observatories build up gradually, being complemented over the years with new telescopes or receiving upgrades for cameras, spectrographs, receivers, correlators and other instrumentation. All these evolutions are difficult to reconstruct *a posteriori*, hence we take the approach to gather as much information as possible, but without the requirement to be complete, leaving out information when it is not available, so that our estimate is formally only a lower limit to the true carbon footprint of ground-based observatories. The results are summarised in Supplementary Table 2.

In our list, there are a number of 1–2 metre class telescopes that are used by IRAP's stellar astrophysics group and for which reliable cost information is in general not available. Several authors have however pointed out that construction cost scales with aperture size D, and for telescopes of modest size [31] suggest that

$$\text{Construction cost} = 1.0 \times D^{2.58} \text{ M€} \tag{1}$$

when converted to 2019 economic conditions, where D is in units of metres. Modern 1-metre class projects still satisfy this scaling law (e.g. [32]), hence we adopt it for construction cost estimation for 1–2 metre class telescopes if no cost information could be found. In the absence of information on operating costs, we furthermore assume 10% of construction cost as annual operating costs, inferred from [33] for telescopes with 1–10 M€ construction cost.

We assembled construction costs and operation costs of observatories from public documents or via private inquiry. All cost values were corrected for inflation and converted to 2019 economic conditions. For IRAM, we could not obtain construction costs for the initial installation, so we take the construction cost of the NOEMA upgrade as a lower limit to the total construction cost. We included the SOFIA airborne observatory in our list of ground-based observatories, since its lifecycle is closer to that of a ground-based observatory than a space mission. For the Event Horizon Telescope (EHT), which is a very long baseline interferometry array of existing millimeter and submillimeter wavelength facilities that span the globe [34], we do not count the carbon footprint of the individual facilities, but the footprint related to the cost of combining the facilities into an Earth-wide VLBI project. For H.E.S.S., the operating costs are full costs

Supplementary Table 1: Payload launch mass and mission cost estimates for the space missions considered in this work. For a few missions no cost estimates could be found, the corresponding entries in the tables are blank.

Mission	Payload launch mass (kg)	Mission cost (M€)	Reference
HST	11 110	8 037	[1]
Chandra	5 860	4 114	[2]
Cassini	5 820	2 806	[3]
Cluster	4 800	944	[4]
Fermi	4 303	863	[5]
INTEGRAL	4 000	419	[6]
Curiosity	3 893	2 590	[3]
XMM	3 800	1 113	[7]
Juno	3 625	1 082	[3]
Herschel	3 400	1 152	[8]
RXTE	3 200	360	[9]
SDO	3 100	865	[10]
Rosetta	2 900	1 709	[11]
Galileo	2 560	1 275	[3]
MAVEN	2 454	638	[3]
ROSAT	2 421	635	[12]
MRO	2 180	928	[3]
GAIA	2 034	1 037	[13]
Planck	1 900	775	[14]
SoHO	1 850	1 469	[15]
Suzaku	1 706		
AstroSat	1 515	27	[17]
MMS	1 360	1 054	[16]
Venus Express	1 270	300	[19]
WIND	1 250		
STEREO	1 238	614	[18]
Mars Express	1 223	374	[20]
Dawn	1 218	439	[3]
Hipparcos	1 140	933	[21]
Kepler	1 052	636	[22]
GEOTAIL	1 009		
Akari	952	106	[23]
Spitzer	950	1 188	[24]
SWIFT	843	279	[25]
ACE	752		
InSight	694	714	[3]
PSP	685	1 310	[1]
WISE	661	335	[26]
TIMED	660	259	[25]
Double Star	560		
IMP-8	410		
NICER	372	53	[27]
NuSTAR	360	156	[28]
TESS	325	275	[29]
GALEX	280	120	[25]
DEMETER	130	21	[30]

extrapolated from the values provided by [35] for France and assuming a French contribution of 28% to the project, estimated from the fraction of French authors on the paper [36].

Supplementary Table 2: Construction and annual operating costs for ground-based astronomical observatories or telescopes that were considered in this work. If no cost estimates could be found the corresponding entries in the table are blank.

Observatory	Cost			
	Construction		Operations	
	(M€)	Reference	(M€ / yr)	Reference
VLT (Paranal)	1 384	[37]	40	[38]
ALMA	1 248	[39]	105	[40]
SOFIA	1 098	[16]	90	[16]
AAT	124	[41]	15	[42]
VLA	345	[33]	10	[43]
VLBA	132	[44]	15	[44]
IRAM	51	[45]	15	[46]
Gemini-South	135	[33]	13	[33]
CFHT	85	[37]	6.3	[47]
ESO 3.6m (La Silla)	99	[48]	5.2	[48]
GBT	120	[49]	10	[50]
LOFAR	200	[51]	9.2	[52]
JCMT	38	[53]	5.5	[54]
ATCA	95	[55]	3.5	[56]
H.E.S.S.	49	(1)	8.8	[35]
MeerKAT	128	[57]	13	[57]
GTC	125	[37]		
NRO	51	(1)	1.5	(1)
LMT	77	[58]	3.1	[59]
MLSO			1.2	[60]
APEX	20	(1)	2.7	[61]
SMA	60	[62]		
EHT	52	[63]	-	-
Noto Radio Observatory			1.5	[64]
2m TBL	6.0	(2)	1.0	[65]
2.16m (Xinglong Station)	7.3	(2)	0.7	(3)
1.93m OHP	5.5	(2)	0.5	(3)
KMTNet	17	(1)	1.7	(1)
THEMIS			1.1	(1)
2.4m LiJiang (YAO)	9.6	(2)	1.0	(3)
2m HCT (IAO)	6.1	(2)	0.6	(3)
1.5m Tillinghast (FLWO)	2.8	(2)	0.3	(3)
1.5m (OAN-SPM)	2.8	(2)	0.3	(3)
1.8m (BOAO)	4.6	(2)	0.5	(3)
1m (Pic-du-Midi)	1.0	(2)	0.1	(3)
1.3m Warsaw (OGLE)	2.0	(2)	0.2	(3)
C2PU	2.0	(2)	0.2	(3)
TAROT	0.9	(1)	0.1	(3)
1m NOWT	1.0	(2)	0.1	(3)

(1) private communication, (2) derived using Eq. (1), (3) assuming 10% of construction cost as annual operation costs.

2 Contribution to the carbon footprint of IRAP

To assess the carbon footprint of astronomical research infrastructures that can be attributed to an individual research institute we select our own institute IRAP as a case study. As a first method of attribution, we use the number of peer-reviewed scientific publications that have authors affiliated to IRAP. This is the method used to assess the scientific productivity of our institute in official evaluations. For this estimate, we used the same ADS queries that we used for the determination of the number of papers for a given research infrastructure, but now we restricted the query to publications that included IRAP among the affiliations, to papers written in 2019, and to the facilities considered in this work. Multiplying the results with the carbon intensity per paper for each space mission and ground-based observatory and summing up the results gives a footprint of 20 ± 4 kt CO_2e (mass-based) to 24 ± 5 kt CO_2e (cost-based) for the space missions and 13 ± 5 kt CO_2e for the ground-based observatories, totalling to 35 ± 7 kt CO_2e for IRAP.

We note, however, that research infrastructures that started operating only recently have a relatively large carbon intensity due to the short period over which the construction footprint is distributed, leading to an artificially inflated carbon footprint attribution. We therefore use an alternative attribution method where we multiply the annual carbon footprint of an infrastructure with the fraction of peer-reviewed papers in 2019 that have authors affiliated to IRAP. This results in a footprint of 12 ± 2 kt CO_2e (mass-based and cost-based) for the space missions and 8 ± 3 kt CO_2e for the ground-based observatories, totalling to 20 ± 3 kt CO_2e for IRAP in 2019. Attributing this footprint equally to the 144 astronomers with PhD degree that worked at IRAP in 2019 results in 139 ± 23 t CO_2e per astronomer. If we instead divide the annual research infrastructure carbon footprint equally by the total number of staff that worked at IRAP in 2019 (263 people), we obtain 76 ± 12 t CO_2e per IRAP staff member.

We want to point out that this attribution method does not provide IRAP's share of the total carbon footprint of research infrastructures among all existing astronomical institutes in the world. Since scientific articles are often signed by authors from multiple institutes, each of these institutes will get the same attribution, implying that the sum of all attributions will exceed the total carbon footprint of all research infrastructures. The share can however be estimated by replacing the number of peer-reviewed papers by the number of unique authors, i.e. multiply the annual carbon footprint of an infrastructure with the fraction of unique authors of peer-reviewed papers in 2019 that are affiliated to IRAP. This results in a carbon footprint of 2.5 ± 0.5 kt CO_2e (mass-based) and 2.8 ± 0.6 kt CO_2e (cost-based) for the space missions, and 1.3 ± 0.5 kt CO_2e for the ground-based observatories, totalling to 4.0 ± 0.7 kt CO_2e for IRAP in 2019. For each of the IRAP astronomers with PhD degree this corresponds to a footprint of 27.4 ± 4.8 t CO_2e, for each person working at IRAP in 2019, the footprint is 15.0 ± 2.6 t CO_2e. We note that also in this share some double-counting may occur since an individual may be affiliated to multiple institutes. But for a given individual, the computation of the share should be accurate.

We point out that this result only covers the research infrastructures considered in this paper. We assembled the list of infrastructures in our sample by scrutinising the titles and abstracts of the 2019 papers affiliated to IRAP, potentially missing infrastructures that were only mentioned in the body text of the papers. Our ADS queries, however, scan the full text of the papers, and hence would lead to a larger contribution to the IRAP footprint if more research infrastructures were covered. To test this hypothesis, we also estimate the IRAP 2019 contribution for all active space missions in 2019, based on the payload mass, and for all active optical-near-infrared (OIR) telescopes with at least 3 metres of diameter. The full list of facilities that we considered is provided in the Supplementary Data file that is available for download at `https://doi.org/10.5281/zenodo.5835840`. In both cases, the extension of the list of infrastructures led to an increase of about 30% in the attributed carbon footprint. If the same holds for other active infrastructures not included in this paper, the footprint of each IRAP astronomer with PhD degree would increase to about 36 t CO_2e.

3 Is offsetting a solution?

A possible solution that is often mentioned in the context of carbon footprint reductions is offsetting. Briefly, offsetting is a process where someone else is paid to reduce his/her carbon footprint in place of yours. Offsetting is already implemented in the European Union Emission Trading Scheme (EU ETS) but so far its impact on reducing the EU GHG emissions is at most modest [69, 70]. At the time of writing the paper (September 2021), the EU ETS carbon price was at 61 € per tonne of CO_2 [67], which expressed in allowed CO_2 emissions per amount of money spent corresponds to 16 400 t CO_2e / M€. Individual offsetting projects have prices of the same order of magnitude, for example atmosfair, a popular scheme in Germany, uses 23 € per tonne of CO_2 at the time of writing the paper [68], corresponding to an allowance of 43 500 t CO_2e / M€. In other words, the allowance to emit CO_2 is about two orders of magnitude larger than the actual emissions for a given amount of money (see the emission factors in Table 1). Therefore the economic incentive to reduce CO_2 emissions by offsetting is basically zero.

Is it possible to take a given amount of CO_2 out of the atmosphere for 100 times less money than was spent for emitting it? As an example, we consider reforestation, which is a popular target of offsetting plans. Reforestation of one hectare of forest costs about 3 k€ [71]. Depending on the prior use of the land, transforming agricultural land to forest brings an additional carbon sequestration of 1.6 t CO_2e per hectare and year, replacing a meadow by a forest brings an additional sequestration of 370 kg CO_2e per hectare and year [72]. In general, using agricultural land for reforestation should be avoided as the land is needed for food production, creating in particular strong ethical issues when offsetting plans are implemented in the Global South. Instead, we consider the sequestration potential of forests replacing meadows. Absorbing for example the ALMA operations footprint of 26 kt CO_2e / yr would require planting 70 000 hectares of forest, which would correspond to an investment of 210 M€. Additionally absorbing its construction footprint of 300 kt CO_2e over a decade (the time scale suggested by the IPCC [66] to reach net zero GHG emissions) needs an additional 81 000 hectares of forest, corresponding to an investment of 240 M€, resulting in a total investment of 450 M€ for offsetting ALMA's GHG emissions. This is about half of ALMA's construction costs, and requires reforestation of an area that is about the size of Monaco. The true price for offsetting is therefore significant, commensurable with the cost to build an astronomical research infrastructure, and it requires the availability of large areas of land that are not yet used otherwise. Real offsetting (i.e. the kind of offsetting we just described) might be a viable temporal solution if other GHG reduction schemes cannot be implemented, but we emphasise it requires considerable investment, which would need to factored into project costs as early as possible.

References

[1] Cangi, E., Gibson, J., & Luebbers, M. Mission costs: Past, Present, Future. *Humans to Moon and Mars Seminar* (2019) https://lasp.colorado.edu/home/mop/files/2019/11/Mission-costs.pdf.

[2] Q&A Chandra mission: How much did Chandra cost? (2021) https://chandra.harvard.edu/resources/faq/chandra/chandra-8.html, consulted on 4/8/2021.

[3] Dreyer, C. The Planetary Exploration Budget Dataset - Missions Overview (2002) https://www.planetary.org/space-policy/planetary-exploration-budget-dataset, consulted on 5/8/2021.

[4] Credland, J. The Cluster Mission - ESA's Space Fleet to the Magnetosphere. *ESA Bulletin Nr. 84.* (1995).

[5] Hertz, P. Astrophysics Large Scale Missions. (2016) https://sites.nationalacademies.org/cs/groups/ssbsite/documents/webpage/ssb_175761.pdf.

[6] Parmer, A., & Winkler, C. INTEGRAL factsheet. *ESA Media Relations* (2011) https://www.esa.int/esaSC/SEM9P5374OD_0_spk.html.

[7] XMM-Newton factsheet. (2021) https://www.esa.int/Science_Exploration/Space_Science/XMM-Newton_factsheet, consulted on 4/8/2021.

[8] Pilbratt, G., & Riedinger, J. Herschel fact sheet. *ESA Media Relations Office* (2010) https://www.esa.int/esaSC/SEMJ3WSMTWE_0_spk.html.

[9] Bradt, H. Reflections on the Rossi X-ray timing explorer. (2013) https://space.mit.edu/wp-content/uploads/2019/06/RXTE-Memoir4.pdf.

[10] Solar Dynamics Observatory. (2021) https://fr.wikipedia.org/wiki/Observatoire_de_la_dynamique_solaire, consulted on 14/9/2021.

[11] Jansen, F., Taylor, M., & Accomazzo, A. *ESA Media Relations Office* (2014) https://www.esa.int/Science_Exploration/Space_Science/Rosetta/Rosetta_Media_factsheet.

[12] ROSAT. (2021) https://de.wikipedia.org/wiki/ROSAT, consulted on 14/9/2021.

[13] Frequently Asked Questions about Gaia. (2021) https://www.esa.int/Science_Exploration/Space_Science/Gaia/Frequently_Asked_Questions_about_Gaia, consulted on 14/9/2021.

[14] Texier, D., & Tauber, J. Planck fact sheet. *ESA Media Relations Office* (2012) https://www.esa.int/esaSC/SEM9WJ0XDYD_0_spk.html, consulted on 14/9/2021.

[15] Fleck, B. SoHO fact sheet. (2003) https://www.nasa.gov/pdf/156578main_SOHO_Fact_Sheet.pdf, consulted on 14/9/2021.

[16] Assessments of Selected Large-Scale Projects. *GAO-12-207SP* (2012) https://www.gao.gov/assets/gao-12-207sp.pdf.

[17] Jayaraman, K. S. India places astronomy observatory in space. *Nature India* (2015) https://www.natureasia.com/en/nindia/article/10.1038/nindia.2015.131.

[18] Kucera, T. STEREO frequently asked questions. (2021) https://stereo.gsfc.nasa.gov/classroom/faq.shtml#COSTS, consulted on 14/9/2021.

[19] Williams, D. R. Venus Express. *NSSDCA/COSPAR ID: 2005-045A* (2021) https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=2005-045A, consulted on 5/8/2021.

[20] Martin, P., Witasse, O., Denis, M., & Martin, P. Mars Express fact sheet. *ESA Media Relations Office* (2013) https://www.esa.int/esaSC/SEMTV8374OD_0_spk.html, consulted on 14/9/2021.

[21] Perryman, M. A. C. The Hipparcos and Tycho Catalogues. *ESA, SP-1200* (1997).

[22] Kepler: NASA's First Mission Capable of Finding Earth-Size Planets. *NASA Press-kit* (2009) https://www.nasa.gov/pdf/314125main_Kepler_presskit_2-19_smfile.pdf.

[23] AKARI. (2021) https://nl.wikipedia.org/wiki/AKARI, consulted on 14/9/2021.

[24] Spitzer Space Telescope Quick Facts. (2020) https://www.jpl.nasa.gov/news/press_kits/spitzer/quick-facts/, consulted on 5/8/2021.

[25] Luhmann, J. Principal-Investigator-Led Missions in the Space Sciences. *ISBN 0-309-10070-4* (2006).

[26] Leone D. WISE Telescope To Be Resurrected for Three-year Asteroid Hunt. *Space News* **August 23** (2013) https://spacenews.com/36913wise-telescope-to-be-resurrected-for-three-year-asteroid-hunt/.

[27] Explorer Programm. (2021) https://explorers.gsfc.nasa.gov/missions.html, consulted on 5/8/2021.

[28] NuSTAR press kit. (2012) https://www.jpl.nasa.gov/news/press_kits/NuSTARpresskit.pdf, consulted on 14/9/2021.

[29] Wall, M. NASA's TESS Planet-Hunting Space Telescope Completes Its Primary Mission. *Scientific American* **August 12** (2020). https://www.scientificamerican.com/article/nasa-rsquo-s-tess-planet-hunting-space-telescope-completes-its-primary-mission/.

[30] Buisson, F. The DEMETER Program: A Pathfinder to a High Performance Micro Satellite Line. *17th Annual AIAA/USU Conference on Small Satellites* (2003) https://digitalcommons.usu.edu/smallsat/2003/All2003/.

[31] Humphries, C. M., Reddish, V. C., & Walshaw, D. J. Cost scaling laws and their origin: Design strategy for an optical array telescope. *Proceedings of the IAU Colluquium No. 79: "Very Large Telescopes, their Instrumentation and Programs", Garching, April 9–12, 1984* 379 (1984).

[32] Liu, J., Soria, R., Wu, X.-F., Wo, H., & Shang, Z. The SiTian Project. *Annals of the Brazilian Academy of Sciences* **93** 1 (2021)

[33] Goodrich, R., Dickinson, M., Bernstein, R., Dumas, C., & McCarthy, P. Observatory Operating Costs and Their Relation to Capital Costs. *Bull. Am. Astron. Soc.* **51** 225 (2019).

[34] Akiyama, K., Alberdi, A., Alef, W., Asada, K., Azulay, R., et al. First M87 Event Horizon Telescope Results. II. Array and Instrumentation *Astrophys. J. Lett.* **875** L2 (2019).

[35] Chardonnet, C., Diaz, I., Lemaître, M., & Pinon, L. Synthèse de l'enquête sur les coûts complets et ressources des infrastructures de recherche de la feuille de route nationale 2016. *DGRI/SPFCO/B4* (2016) https://cache.media.enseignementsup-recherche.gouv.fr/file/Infrastructures_de_recherche/76/7/2016_synthese_enquete_1146767.pdf.

[36] Abdalla, H., Adam, R., Aharonian, F., Ait Benkhali, F., Angüner, E.O. et al. Constraints on the emission region of 3C 279 during strong flares in 2015 and 2015 through VHE gamma-ray observations with H.E.S.S. *Astron. Astrophys.* **627**, A159 (2019).

[37] Van Belle, G. T., Meinel, A. B., & Meinel, M. P. The scaling relationship between telescope cost and aperture size for very large telescopes. *Proc. SPIE* **5489**, 563 (2004).

[38] FAQ VLT/Paranal. (2021) https://www.eso.org/public/about-eso/faq/faq-vlt-paranal/, consulted on 4/8/2021.

[39] ALMA factsheet (2021) https://www.almaobservatory.org/en/factsheet/, consulted on 4/8/2021.

[40] Mountain, M., & Cohen, A. US astronomers face hard decisions. *Nature* **560**, 427 (2018).

[41] Brief history of AAT. (2021) https://aat.anu.edu.au/about-us/a-brief-history, consulted on 4/8/2021.

[42] Colless, M. Annual Report of the Anglo-Australian Observatory, 1 July 2009 – 30 June 2021. (2009) https://aat.anu.edu.au/about-us/annual-reports.

[43] NSF Fiscal Year 2019 Budget Request for the National Optical Astronomy Observatory (NOAO). (2019) https://www.nsf.gov/about/budget/fy2019/pdf/40s_fy2019.pdf

[44] Very Long Baseline Array. (2021) https://en.wikipedia.org/wiki/Very_Long_Baseline_Array, consulted on 4/8/2021.

[45] Une étape majeure pour la construction du radiotélescope NOEMA. (2021) https://www.iram-institute.org/EN/news/2018/163.html, consulted on 4/8/2021.

[46] Pety, J., Lagache, G., Gerin, M., Demyk, K., Elbaz, D., et al. IRAM-France Day summary note. (2019) https://iram-france.sciencesconf.org/data/pages/iram_france_summary.pdf, consulted on 4/8/2021.

[47] 2019 CFHT Annual Report. (2019) https://www.cfht.hawaii.edu/en/about/AnnualReports.php.

[48] Lodewijk, W., Europe's Quest for The Universe. *EDP Sciences* ISBN-10 2868838138 (2006)

[49] Green Bank Facts. (2021) https://greenbankobservatory.org/about/green-bank-facts/, consulted on 4/8/2021.

[50] Advancing Astronomy in the Coming Decade: Opportunities and Challenges. Report of the National Science Foundation Division of Astronomical Sciences Portfolio Review Committee. (2012) https://www.nsf.gov/mps/ast/portfolioreview/reports/ast_portfolio_review_report.pdf

[51] LOFAR-UK statement on STFC Science Programme Prioritisation 2010-2015. https://lofar-uk.org/images/lofar-uk-stfc-response.pdf.

[52] LOFAR: opening a window on the low frequency radio Universe. (2005) https://lesia.obspm.fr/plasma/LOFAR2006/LOFAR_ESFRI_24nov05.pdf.

[53] Hill, R. A Personal Retrospective. *JCMT Newsletter* **36** (2015). https://www.eaobservatory.org//JCMT/publications/newsletter/jcmt-n36.pdf.

[54] Davis, G. The James Clerk Maxwell Telescope Prospectus. (2021) https://stfc.ukri.org/files/jcmtprospectuspdf/, consulted on 8/8/2021.

[55] Building the Australia Telescope Compact Array. (2021) https://www.atnf.csiro.au/outreach/about/history/building-atca/index.html, consulted on 4/8/2021.

[56] Bock, D. ATNF Operations. (2015) https://www.atnf.csiro.au/management/atuc/presentation/jun2015_Bock_ATNF_Ops.pdf.

[57] Maseko, L. Meeting Summary of National Assembly Science and Technology committee. (2017) https://pmg.org.za/committee-meeting/24534/, consulted on 4/8/2021.

[58] Leverington, D. Observatories and Telescopes of Modern Times: Ground-Based Optical and Radio Astronomy Facilities since 1945. *Cambridge: Cambridge University Press. doi:10.1017/9781139051507* (2016)

[59] Schloerb, P., Aretxaga, I., Chavez, M., Gutermuth, R., Heyer, M., et al. A Decade of US Community Access to the Large Millimeter Telescope Alfonso Serrano. *Bull. Am. Astron. Soc.* **51**, 148 (2019).

[60] McIntosh, S., Tomczyk, S., Gibson, S. E., Burkepile, J., de Wijn, A., et al. Investigating Coronal Magnetism with COSMO: Science on the Critical Path To Understanding The Weather of Stars and Stellarspheres. *Bull. Am. Astron. Soc.* **51**, 165 (2019).

[61] Olofsson, H. Strategic Plan 2012-2016: Onsala Space Observatory. The Swedish National Facility for Radio Astronomy. (2012)

[62] Masson, C. Submillimeter Array Technical Memorandum #29. *Harvard, Smithsonian Center for Astrophysics* (1990).

[63] Borenstein, S. First black hole picture: Event Horizon Telescope project reveals historic image. *ABC7News* **April 11** (2019) https://abc7news.com/black-hole-picture-photo-of/5241612/.

[64] Wijers, R. et al. Radio Astronomy in Europe: Up to, and beyond, 2025. *Final report of the European Radio Telescope Review Committee (ERTRC)* (2015) https://www.radionet-org.eu/radionet/wp-content/uploads/sites/15/2017/03/150713-ASTRONET-ERTRC-Report-Final.pdf.

[65] Cabanac, R. Telescope Bernard Lyot: operation, instrumentation, perspectives. *SF2A-2016: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics, eds. Reylé, C., Richard, J., Cambrésy, L., Deleuil, M., and Pécontal, E., Tresse, L., & Vauglin, I.*, 237 (2016).

[66] IPCC, 2021: Summary for Policymakers. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press.*

[67] Daily Carbon Prices. (2021) https://ember-climate.org/data/carbon-price-viewer/, consulted on 13/9/2021.

[68] Offset a desired amount of CO_2. (2021) https://www.atmosfair.de/en/offset/fix/, consulted on 13/9/2021.

[69] Bayer, P., & Aklin, Michaël The European Union Emissions Trading System reduced CO_2 emissions despite low prices. *Proc. Natl Acad. Sci. USA* **117** 16, 8804 (2020).

[70] Lehne, J., Moro, E., Nguyen, P.-V., Pellerin-Carlin, T. The EU ETS: From cornerstone to catalyst. *E3G, Jaques Delors Institut* (2021) https://institutdelors.eu/wp-content/uploads/2021/04/JDI-E3G-paper_innovation-in-the-ETS_final.pdf.

[71] Reforestation", Agriculture and Food Development Authority. (2021) https://www.teagasc.ie/crops/forestry/advice/establishment/reforestation/, consulted on 13/9/2021.

[72] Breitenstein, A. Base Carbone. https://www.bilans-ges.ademe.fr/fr/basecarbone/donnees-consulter/choix-categorie.