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Estimate of the carbon footprint of astronomical research infrastructures

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The carbon footprint of astronomical research is an increasingly topical issue with first estimates of research institute and national community footprints having recently been published. As these assessments have typically excluded the contribution of astronomical research infrastructures, we complement these studies by providing an estimate of the contribution of astronomical space missions and ground-based observatories using greenhouse gas emission factors that relates cost and payload mass to carbon footprint. We find that worldwide active astronomical research infrastructures currently have a carbon footprint of 20.3 ± 3.3 MtCO₂ equivalent (CO₂e) and an annual emission of $1,169 \pm 249$ ktCO₂e yr⁻¹ corresponding to a footprint of 36.6 ± 14.0 tCO₂e per year per astronomer. Compared with contributions from other aspects of astronomy research activity, our results suggest that research infrastructures make the single largest contribution to the carbon footprint of an astronomer. We discuss the limitations and uncertainties of our method and explore measures that can bring greenhouse gas emissions from astronomical research infrastructures towards a sustainable level.

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) Working Group I could not be more explicit: “It is unequivocal that human influence has warmed the atmosphere, ocean and land [...] Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in CO₂ and other greenhouse gas emissions occur in the coming decades.”¹. As stated by António Guterres, United Nations Secretary-General, the IPCC Sixth

Assessment Report is a “code red for humanity”².

Taking up this code-red alert, there is growing recognition in the astrophysics community that it must assume its share of the global effort to reduce greenhouse gases (GHGs)³⁻⁶. Much recent attention has focused on the reduction of academic flying⁷⁻¹¹ and, to a lesser extent, on the use of supercomputers^{6,12}. Quantifying the GHG emissions due to the construction and operation of space observatories, planetary probes and ground-based observatories has so far attracted less attention. With the decades-long lifetime of research infrastructures, decisions that are made now will lock in GHG emissions of the astrophysics community for the next decades, potentially compromising the goal to reach net-zero emissions by the middle of this century. Assessments of the environmental footprint of existing and future astronomical facilities are therefore urgently needed.

To address this gap, we have developed a method that provides a first-order estimate of the carbon footprint of astronomical research infrastructures (see ‘Carbon footprint estimation’ in Methods). We estimate the carbon footprint of each facility using the standard method of multiplying activity data with emission factors. Detailed activity data (for example, MWh of electricity consumed for construction of a satellite or tonnes of concrete poured for the foundation of a telescope) are generally not publicly available for astronomical research infrastructures, so we use aggregated activity data based on cost and mass for our analysis. Specifically, we use the full mission cost and payload launch mass for space missions and the construction and operating costs for ground-based observatories (Supplementary Tables 1 and 2).

Using cost data to estimate a project’s carbon footprint is referred to as economic input–output (EIO) analysis. This approach is known to have large uncertainties due to the aggregation of activities, products and monetary flows that may vary considerably from one facility or field of activity to another. An alternative life-cycle assessment (LCA) methodology is recommended by key space industry actors (for example, ref. 13) as the optimal method to assess and reduce the carbon footprint of space missions, but it is difficult to implement in practice (especially for comparative or discipline-wide assessments) due to the confidential nature of the required input activity data¹⁴. At present, an EIO analysis is thus the only feasible way to assess the combined carbon footprint of the world’s space- and ground-based astronomical research infrastructures. We

adopt throughout this study an uncertainty of 80% for the carbon footprint estimate of individual facilities, as recommended by the French Agency for Ecological Transition (ADEME) for an EIO analysis¹⁵.

Detailed carbon footprint assessments do exist for a handful of facilities, and we use these assessments to derive dedicated emission factors for our analysis. We emphasize that our results in this paper are order-of-magnitude estimates that may differ by a factor of a few from the true carbon footprint of any given facility. We propagate uncertainties throughout our analysis and the aggregated results and their associated uncertainties are robust. We note that our total and per-astronomer estimates are likely to be conservative, since we simply excluded any activity data that we could not locate, and our estimate for the number of astronomers in the world is probably an upper limit (see ‘The number of astronomers in the world’ in Methods). The average carbon footprint of astronomical research infrastructures per astronomer is thus likely to be larger than our estimate, or towards the upper bound of our quoted uncertainty interval.

Our work was conducted in the context of the carbon footprint assessment of our institute, the Institut de Recherche en Astrophysique et Planétologie (IRAP) for the year 2019 and hence we adopt 2019 as the reference year for our study. Specifically, all cost data have been corrected for inflation and are expressed in 2019 economic conditions. We based our work on a list of 46 space missions and 39 ground-based observatories from which data were used to produce peer-reviewed journal articles authored or co-authored by IRAP scientists in 2019. Extrapolating the results for this list to all active astronomical research infrastructures in the world yields an estimate for the worldwide carbon footprint of astronomical facilities.

Results

To estimate emission factors for astronomical research infrastructures, we made a comprehensive search for published carbon footprint assessment reports. As detailed in ‘Emission factors’ in Methods, these reports are currently very scarce. We found two case studies for life-cycle carbon footprints of space missions, which covered the entire mission including the launcher and a few years of operations¹⁶. From these studies, we infer mean emission factors of 140 tCO₂ equivalent (CO₂e) per million € (M€) of mission cost and 50 tCO₂e kg⁻¹ of payload launch mass. Emission

factors of ground-based observatories were derived using existing carbon footprint assessments for the construction of two facilities and the operations of three facilities. We find a mean emission factor of $240 \text{ tCO}_2\text{e M}\text{€}^{-1}$ for construction and of $250 \text{ tCO}_2\text{e M}\text{€}^{-1}$ for operations. The emission factors are summarized in Table 1. The lower monetary emission factor for space missions compared with ground-based observatories can be attributed to the low production rates, long development cycles and specialized materials and processes of the space sector¹⁷.

Table 2 summarizes order-of-magnitude estimates for the carbon life-cycle footprints of space missions based on payload launch mass and mission cost (see ‘Carbon footprint estimation’ and ‘Emission factors’ in Methods and Supplementary Tables 1 and 2). The cost-based estimates are on average about 20% larger than the mass-based estimates, probably because mission complexity and mission extensions are not taken into account by the latter. Examples include the Hubble Space Telescope (HST), which had five Space Shuttle servicing missions that are included in the cost-based estimate but not in the mass-based estimate, and the Mars rover Curiosity, for which the mission complexity is not properly reflected in the mass-based estimate.

For some missions, the mass-based estimates are larger. In some cases, this can be explained by lower mission complexity, but it may also be due to underestimates of the true costs. For example, the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) makes use of the same satellite bus as the X-ray Multi-Mirror mission (XMM-Newton), which led to important cost savings. On the other hand, the quoted cost estimate for INTEGRAL only covers the mission cost to the European Space Agency (ESA), excluding the payload cost and the launcher cost, the latter having been provided by Russia in exchange for observing time. The Cluster mission consists of four identical spacecrafts and shares the same launcher for all four satellites, which also results in a relatively low cost-to-mass ratio. We also note that cost estimates for the Astronomy Satellite (AstroSat) and Akari appear to be substantially underestimated.

We consider that using both mass-based and cost-based estimates gives a good indication of the typical uncertainty that is inherent to our approach. ESA advises against using EIO analyses due to their large inherent uncertainties¹³, yet our analysis suggests that as long as the uncertainties are properly considered, an EIO analysis for space missions yields results that are comparable with an

analysis based on payload mass. Summing the carbon footprint estimates for the 40 space missions that have both mass-based and cost-based estimates yields 4.6 ± 0.8 MtCO₂e for the mass-based and 5.9 ± 1.2 MtCO₂e for the cost-based estimates, where errors reflect the adopted uncertainty of 80% in the carbon footprint of each individual space mission (uncertainties for individual facilities are added in quadrature through the paper by taking the square root of the sum of uncertainty squares). Summing the mass-based estimates for all 46 space missions increases the total carbon footprint by 6% to 4.9 ± 0.8 MtCO₂e. Assuming that the same increase would apply to the remaining 6 space missions for which we did not find any cost estimates would lead to a cost-based estimate of 6.2 ± 1.3 MtCO₂e. Table 2 also lists the annual footprints of the facilities, computed by dividing the life-cycle footprints by the lifetime of the mission, defined as the time since launch or ten years, whichever is longer (see ‘Annual footprint’ in Methods). The total annual footprint of the missions in Table 2 is 310 ± 47 ktCO₂e yr⁻¹ for the mass-based and 366 ± 64 ktCO₂e yr⁻¹ for the cost-based estimates.

Order-of-magnitude estimates for the carbon life-cycle footprints of ground-based observatories are summarized in Table 3. After a few decades, the operations footprint dominates the life-cycle footprint. The life-cycle carbon footprint of the ground-based observatories listed in Table 3 is estimated to be 3.0 ± 0.8 MtCO₂e, with a total footprint for construction of 1.4 ± 0.4 MtCO₂e (46%) and for operations of 1.6 ± 0.4 MtCO₂e (54%). The total annual carbon footprint amounts to 194 ± 64 ktCO₂e yr⁻¹ for the ground-based observatories in Table 3.

To put the results in perspective, we compute the carbon intensity of each infrastructure, defined as the lifetime footprint divided by either the number of peer-reviewed papers or the number of unique authors (see ‘Carbon intensity’ in Methods). The meaning of these quantities is that they relate the total carbon footprint of a given infrastructure to the scientific productivity of the community and to the size of the community that makes use of it. Specifically, the latter provides a measure of how the infrastructure footprint is shared among the user community.

The results of this computation are shown in Tables 2 and 3 and further illustrated in Fig. 1, which shows the carbon intensities as function of a facility’s lifetime. While there is an overall envelope of decreasing carbon intensities with time, not all facilities start with a large carbon intensity and some

Table 1: Adopted emission factors.

Activity	Emission factor
Space missions (per payload launch mass)	50 tCO ₂ e kg ⁻¹
Space missions (per mission full cost)	140 tCO ₂ e M€ ⁻¹
Ground-based observatory construction	240 tCO ₂ e M€ ⁻¹
Ground-based operations	250 tCO ₂ e M€ ⁻¹

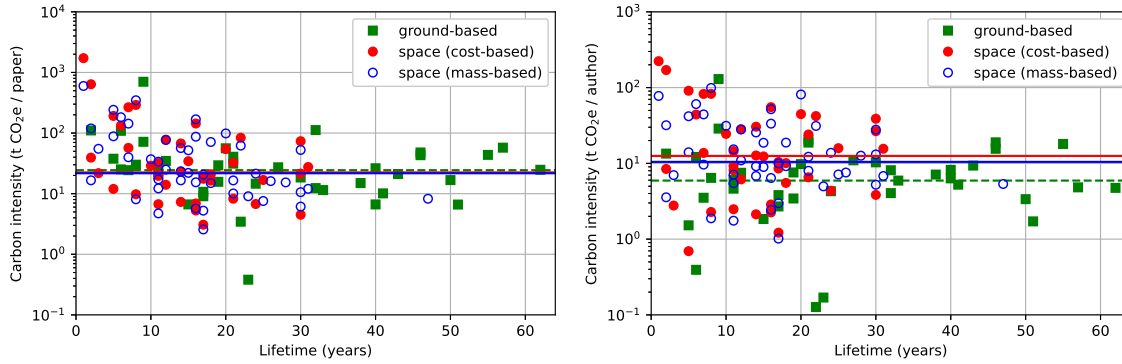


Figure 1: **Carbon intensity versus time since launch or start of operations for space missions and ground-based observatories.** Open blue circles are for mass-based estimates and filled red circles are for cost-based estimates of space missions. Green squares represent ground-based observatories. The left panel shows the carbon intensity per peer-reviewed paper and the right panel shows the carbon intensity per unique author. The horizontal lines indicate the median carbon intensities.

Table 2: Order of magnitude estimates of the carbon footprints of some selected space missions, ordered by decreasing mass-based footprint. For cells that are blank no cost estimates could be found.

Mission	Years	Papers	Authors	Mass-based				Cost-based			
				total since launch			Footprint	Annual	Carbon intensity		Footprint
				(tCO ₂ e)	(tCO ₂ e yr ⁻¹)	(tCO ₂ e per paper)	(tCO ₂ e per author)	(tCO ₂ e)	(tCO ₂ e yr ⁻¹)	(tCO ₂ e per paper)	(tCO ₂ e per author)
HST	30	52,497	42,315	555,500	18,517	11	13	1,125,197	37,507	21	27
Chandra	21	17,714	23,942	293,000	13,952	17	12	575,955	27,426	33	24
Cassini	22	4,691	9,328	291,000	13,227	62	31	392,902	17,859	84	42
Cluster	20	2,433	2,959	240,000	12,000	99	81	132,207	6,610	54	45
Fermi	12	8,619	19,675	215,150	17,929	25	11	120,881	10,073	14	6
INTEGRAL	18	2,808	10,640	200,000	11,111	71	19	58,720	3,262	21	6
Curiosity	7	1,360	4,393	194,650	19,465	143	44	362,595	36,259	267	83
XMM	21	18,859	23,773	190,000	9,048	10	8	155,845	7,421	8	7
Juno	8	521	1,832	181,250	18,125	348	99	151,547	15,155	291	83
Herschel	11	5,046	11,092	170,000	15,455	34	15	161,238	14,658	32	15
RXTE	24	7,473	11,601	160,000	6,667	21	14	50,438	2,102	7	4
SDO	10	4,189	4,946	155,000	15,500	37	31	121,164	12,116	29	24
Rosetta	16	1,665	4,337	145,000	9,063	87	33	239,316	14,957	144	55
Galileo	30	2,432	4,594	128,000	4,267	53	28	178,503	5,950	73	39
MAVEN	6	672	2,023	122,700	12,270	183	61	89,270	8,927	133	44
ROSAT	30	19,765	23,154	121,050	4,035	6	5	88,844	2,961	4	4
MRO	14	1,927	4,261	109,000	7,786	57	26	129,850	9,275	67	30
Gaia	7	2,550	10,565	101,700	10,170	40	10	145,114	14,511	57	14
Planck	11	5,515	13,388	95,000	8,636	17	7	108,486	9,862	20	8
SoHO	25	12,218	12,955	92,500	3,700	8	7	205,617	8,225	17	16
Suzaku	15	3,869	9,525	85,300	5,687	22	9				
AstroSat	5	313	5,406	75,750	7,575	242	14	3,751	375	12	1
MMS	5	769	1,623	68,000	6,800	88	42	147,501	14,750	192	91
Venus Express	15	1,221	3,394	63,500	4,233	52	19	41,945	2,796	34	12
Wind	26	3,877	8,254	62,500	2,404	16	8				
STEREO	14	3,731	6,768	61,900	4,421	17	9	86,021	6,144	23	13
Mars Express	17	2,969	6,118	61,150	3,597	21	10	52,332	3,078	18	9
Dawn	12	791	2,175	60,885	5,074	77	28	61,409	5,117	78	28
Hipparcos	31	4,743	8,373	57,000	1,839	12	7	130,664	4,215	28	16
Kepler	11	4,306	9,606	52,620	4,784	12	5	89,037	8,094	21	9
Geotail	28	3,288	3,996	50,450	1,802	15	13				
Akari	14	2,037	6,993	47,600	3,400	23	7	14,878	1,063	7	2
Spitzer	17	9,050	15,940	47,500	2,794	5	3	166,333	9,784	18	10
Swift	16	7,397	17,307	42,150	2,634	6	2	39,030	2,439	5	2
ACE	23	4,147	7,560	37,600	1,635	9	5				
InSight	1	58	447	34,700	3,470	598	78	99,922	9,992	1723	224
PSP	2	287	1,075	34,250	3,425	119	32	183,456	18,346	639	171
WISE	11	6,990	18,877	33,050	3,005	5	2	46,855	4,260	7	2
TIMED	18	2,205	3,593	33,000	1,833	15	9	36,196	2,011	16	10
Double Star	16	166	540	28,000	1,750	169	52				
IMP-8	47	2,485	3,835	20,500	436	8	5				
NICER	3	338	2,657	18,600	1,860	55	7	7,374	737	22	3
NuSTAR	8	2,227	9,559	18,000	1,800	8	2	21,799	2,180	10	2
TESS	2	978	4,557	16,250	1,625	17	4	38,478	3,848	39	8
GALEX	17	5,452	13,790	14,000	824	3	1	16,780	987	3	1
DEMETER	16	422	1,014	6,500	406	15	6	2,907	182	7	3

Table 3: Order of magnitude estimates of the carbon footprint of some selected ground-based astronomical observatories or telescopes, ordered by decreasing footprint over the lifetime of the infrastructure. For cells that are blank no cost estimates could be found.

Observatory	Lifetime (yr)	Papers	Authors	Footprint				Carbon intensity	
				Construction (tCO ₂ e)	Operation (tCO ₂ e yr ⁻¹)	Lifetime (tCO ₂ e)	Annual (tCO ₂ e yr ⁻¹)	(tCO ₂ e per paper)	(tCO ₂ e per author)
VLT (Paranal)	21	17,235	26,442	332,280	9,875	539,655	25,698	31	20
ALMA	9	7,460	18,610	299,576	26,196	535,340	56,154	72	29
SOFIA	9	662	3,586	263,544	22,375	464,919	48,729	702	130
AAT	46	4,297	10,848	29,728	3,824	205,610	4,470	48	19
VLA	40	26,918	28,206	82,817	2,400	178,826	4,471	7	6
VLBA	27	4,995	12,427	31,608	3,874	136,194	5,044	27	11
IRAM	30	6,744	12,095	12,240	3,750	124,740	4,158	18	10
Gemini-South	20	1,735	9,949	32,280	3,250	97,280	4,864	56	10
CFHT	41	8,400	16,228	20,414	1,575	84,989	2,073	10	5
ESO 3.6m (La Silla)	43	3,774	8,515	23,815	1,298	79,608	1,851	21	9
GBT	19	2,554	9,905	28,812	2,436	75,088	3,952	29	8
LOFAR	8	2,205	10,304	48,000	2,291	66,326	7,091	30	6
JCMT	33	4,726	9,145	9,192	1,364	54,194	1,642	11	6
ATCA	32	4,108	12,537	22,863	873	50,787	1,587	12	4
H.E.S.S.	17	4,577	12,889	11,848	2,193	49,126	2,890	11	4
MeerKAT	2	335	2,750	30,624	3,190	37,004	6,252	110	13
GTC	11	1,059	6,445	29,880		29,880	2,716	28	5
NRO	38	1,776	3,739	12,233	378	26,609	700	15	7
LMT	6	213	1,912	18,504	786	23,221	2,637	109	12
MLSO	55	385	932		306	16,817	306	44	18
APEX	15	2,244	8,097	4,800	675	14,925	995	7	2
SMA	17	1,585	5,312	14,354		14,354	844	9	3
EHT	11	606	2,079	12,580	-	12,580	1,144	21	6
Noto Radio Observatory	32	108	1,490		378	12,096	378	112	8
2m TBL	40	435	1,392	1,435	250	11,435	286	26	8
2.16m (Xinglong Station)	46	235	651	1,750	182	10,137	220	43	16
1.93m OHP	62	394	2,056	1,309	136	9,763	157	25	5
KMTNet	5	169	4,191	4,193	437	6,377	856	38	2
THEMIS	21	142	307		275	5,775	275	41	19
2.4m LiJiang (YAO)	12	149	688	2,297	239	5,168	431	35	8
2m HCT	19	276	1,259	1,454	151	4,331	228	16	3
1.5m Tillinghast (FLWO)	51	652	2,514	683	71	4,312	85	7	2
1.5m (OAN-SPM)	50	253	1,258	683	71	4,241	85	17	3
1.8m (BOAO)	24	262	892	1,093	114	3,827	159	15	4
1m (Pic-du-Midi)	57	29	345	240	25	1,665	29	57	5
1.3m Warsaw (OGLE)	23	4,210	9,470	472	49	1,604	70	0.4	0.2
C2PU	6	31	1,982	480	50	780	98	25	0.4
TAROT	22	206	5,602	216	23	711	32	3	0.1
1m NOWT	7	17	118	240	25	415	49	24	4

facilities still have an important carbon intensity decades after their launch or start of operations. Since the distribution of carbon intensities among the facilities is obviously heavily skewed, we use the median instead of the mean to estimate a typical value for the facilities. For space missions we find a median carbon intensity of 22 tCO₂e per paper for both the mass-based and cost-based estimates. Ground-based observatories have a comparable median carbon intensity of 24 tCO₂e per paper. When normalized by author, space missions have a median carbon intensity of 10 tCO₂e per author for the mass-based and 13 tCO₂e per author for the cost-based estimates, while ground-based observatories have a median value of 6 tCO₂e per author. This suggests that, on average, more authors are involved in publications citing ground-based observatories compared with publications citing space missions.

To estimate the share of the carbon footprint that should be attributed to an astronomer at our institute, we multiply the annual carbon footprint of each facility with the fraction of unique authors of peer-reviewed papers published in 2019 that are affiliated to IRAP (alternative attribution methods are explored in the Supplementary Information). This results in a carbon footprint of 2.5 ± 0.5 ktCO₂e (mass-based) and 2.8 ± 0.6 ktCO₂e (cost-based) for the space missions and 1.3 ± 0.5 ktCO₂e for the ground-based observatories, totalling 4.0 ± 0.7 ktCO₂e for IRAP in 2019, where the uncertainty includes the difference between the mass- and cost-based estimates. For each of the 144 IRAP astronomers with a PhD degree this corresponds to a footprint of 27.4 ± 4.8 tCO₂e, while for each of the 263 persons working at IRAP in 2019 (that is, including students and all technical and administrative staff) the footprint is 15.0 ± 2.6 tCO₂e. The research infrastructures listed in Tables 2 and 3 are however only a subset of all infrastructures that exist worldwide, hence formally these estimates are lower limits. Correcting for the incompleteness of our subset suggests a footprint of about 36 tCO₂e per IRAP astronomer in 2019 (Supplementary Information).

Based on the results of Tables 2 and 3 and using an estimate for the total number of astronomical research infrastructures that were active in 2019 in the world, we estimate their global carbon footprint using a bootstrap method (see ‘The worldwide footprint of astronomical facilities’ in Methods). While this method assumes that the research infrastructures considered in this paper are representative of all astronomical facilities that exist worldwide, we reduce the bias introduced

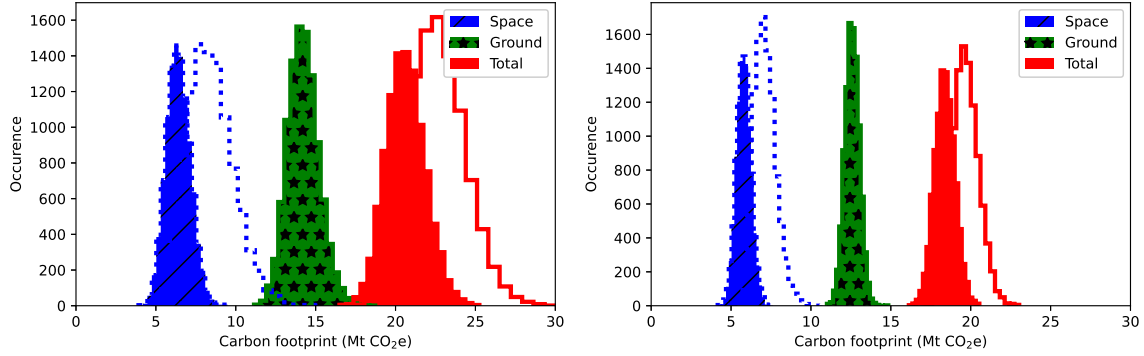


Figure 2: **Distribution of the carbon footprint of astronomical research infrastructures that exist worldwide as derived using the bootstrap method.** The left panel shows the sampling of all facilities, and for the right panel the infrastructure with the largest carbon footprint in each category was excluded from the sampling. For space missions, cost-based estimates are shown as filled histograms and mass-based estimates are shown as unfilled histograms. Estimates for space missions are in blue hatched fill and dotted line, estimates for ground-based observatories are in green fill with stars and total carbon footprint estimates, which is the sum of space and ground-based facilities, are in red uniform fill and solid line.

by the specific selection by dividing all research infrastructures into broad categories that reflect scientific topic or observatory type. The results of this exercise are summarized in Table 4 and the carbon footprint distributions that were obtained by the bootstrapping are shown in Fig. 2.

We find that the world’s fleet of astronomical space missions has a total carbon footprint of 7.4 ± 2.2 MtCO₂e and an annual footprint of 525 ± 184 ktCO₂e yr⁻¹, where the uncertainties include the difference between the mass-based and cost-based estimates. We note that roughly half of the existing space missions are covered by Table 2, with a coverage of 100% for solar missions, between 50%–60% for plasma or astrophysics missions and $\sim 30\%$ for planetary missions. Due to the strong representation of IRAP in many recent space missions, we thus consider that our extrapolation to the full inventory of active space missions worldwide is robust. We estimate the total carbon footprint of all ground-based astronomical observatories as 14.2 ± 1.5 MtCO₂e and their annual footprint to be 757 ± 131 ktCO₂e yr⁻¹. While the total footprint for ground-based observatories is about twice as large as that for space missions, their annual footprint is only about 44% larger, owing to, on

Table 4: Extrapolated carbon footprint of all active astronomical research infrastructures in the world. The number of active facilities in Tables 2 and 3 in a given category are given in column 2, the estimated worldwide number in each category is given in column 3. The sum of the total and annual carbon footprints in each category for the selected infrastructures is given in columns 4 and 5, quoted uncertainties reflect the 80% uncertainty in the footprint of individual facilities. The extrapolated values for worldwide active research infrastructures are given in columns 6 and 7, quoted uncertainties reflect the variance of the bootstrap sampling and the uncertainty of the carbon footprint estimates.

Category	Research Infrastructures		Carbon footprint of selected research infrastructures		Carbon footprint of all research infrastructures	
	Selected	Worldwide	Life cycle (ktCO ₂ e)	Annual (ktCO ₂ e yr ⁻¹)	Life cycle (ktCO ₂ e)	Annual (ktCO ₂ e yr ⁻¹)
Space missions (mass-based)						
Solar	3	3	282±147	23±13	282±166	23±16
Plasma	7	13	553±219	31±12	1,029±375	58±20
Planetary	6	21	703±256	65±25	2,461±546	226±54
Astro	12	18	1,759±586	99±28	2,636±955	149±43
Sum			3,298±692	217±78	6,409±1,174	455±74
Space missions (cost-based)						
Solar	3	3	510±241	39±19	510±247	39±20
Plasma	4	13	402±175	30±14	1,306±352	96±30
Planetary	6	21	886±351	83±34	3,100±798	289±80
Astro	12	18	2,339±1,033	114±41	3,526±1,816	172±68
Sum			4,137±1,131	265±58	8,442±2,030	596±111
Ground-based observatories						
OIR (≥ 3m)	9	37	1,037±478	42±21	4,263±665	171±27
OIR (others)	19	~1000	65±17	3±1	3,409±163	147±6
Radio	6	74	206±81	10±4	2,540±345	127±18
Radio Arrays	9	27	1,156±481	87±46	3,465±1,140	260±115
Others	4	4	537±374	52±39	538±499	52±53
Sum			3,001±779	194±64	14,214±1,461	757±131

average, longer lifetimes for ground-based observatories compared with space missions.

Summing both contributions yields a total carbon footprint of all active astronomical research infrastructures in 2019 of 21.6 ± 3.2 MtCO₂e and an annual footprint of $1,283 \pm 232$ ktCO₂e yr⁻¹, where uncertainties reflect statistical variations introduced by the bootstrap method, the 80% uncertainty in the emission factors for individual facilities and the difference between mass-based and cost-based estimates. By dividing the annual carbon footprint by an assumed world population of 30,000 astronomers with a PhD degree (see ‘The number of astronomers in the world’ in Methods), we obtain an annual footprint of 42.8 ± 7.7 tCO₂e yr⁻¹ per astronomer. Assuming that astronomical institutes worldwide have similar staffing profiles as IRAP, which is roughly one student, technical or administrative personnel per astronomer with a PhD degree, the annual footprint per person working in astronomy in any capacity is roughly half this value.

We reiterate that these are order-of-magnitude estimates, obtained under the assumption that the facilities in Tables 2 and 3 are representative of all astronomical research infrastructures that exist worldwide. Using a modified procedure that avoids resampling of research infrastructures that have no equivalent in the world, such as the HST or the Atacama Large Millimeter/submillimeter Array (ALMA), results in a reduced total carbon footprint of 19.1 ± 2.3 MtCO₂e and annual carbon footprints of $1,054 \pm 138$ ktCO₂e yr⁻¹ and 35.1 ± 4.6 tCO₂e yr⁻¹ per astronomer. Sampling of unique research infrastructures may hence overestimate the annual carbon footprint by about 20%. Averaging the original and the modified bootstrap results and including their difference in the uncertainty yields a total carbon footprint of astronomical research infrastructures of 20.3 ± 3.3 MtCO₂e and an annual carbon footprint of $1,169 \pm 249$ ktCO₂e yr⁻¹ and 39.0 ± 8.3 tCO₂e yr⁻¹ per astronomer.

The two methods we applied to derive the average carbon footprint of research infrastructures per astronomer holding a PhD, either based on more restrictive criteria for IRAP or based on an extrapolation to all active infrastructures for an average astronomer, lead to the same order-of-magnitude estimate. The range of values spanned by both estimates is 36.6 ± 14.0 tCO₂e yr⁻¹, where the uncertainty mainly reflects the differences that are plausibly explained by the method of estimation. While the IRAP result of 27.4 ± 4.8 tCO₂e yr⁻¹ may miss the attribution of the carbon

footprint of some infrastructures that were not considered in this paper, the global extrapolation of $42.8 \pm 7.7 \text{ tCO}_2\text{e yr}^{-1}$ using the original bootstrap method may overestimate the footprint due to the large footprints of a few facilities that are unique in the world.

Comparing our result of $36.6 \pm 14.0 \text{ tCO}_2\text{e yr}^{-1}$ per astronomer for research infrastructures with estimates for other sources of GHG emissions due to astronomy research activity reveals that astronomical research infrastructures dominate the carbon footprint of an average astronomer. For example, excluding research infrastructures, capital goods and the purchase of goods and services, ref. 12 estimated the average carbon footprint of an astronomer at the Max Planck Institut for Astronomy in Heidelberg to be $18.1 \text{ tCO}_2\text{e yr}^{-1}$, dominated by $8.5 \text{ tCO}_2\text{e yr}^{-1}$ from flights, $5.2 \text{ tCO}_2\text{e yr}^{-1}$ from electricity use and $3.0 \text{ tCO}_2\text{e yr}^{-1}$ from heating. For the average Australian astronomer (including PhD students), ref. 6 estimated a footprint of $\geq 37 \text{ tCO}_2\text{e yr}^{-1}$, comprised of $22 \text{ tCO}_2\text{e yr}^{-1}$ for supercomputing, $6 \text{ tCO}_2\text{e yr}^{-1}$ from flights, $4 \text{ tCO}_2\text{e yr}^{-1}$ for powering the office buildings and $5 \text{ tCO}_2\text{e yr}^{-1}$ for powering ground-based observatories in Australia. All of these individual contributions are below our estimate for the contribution of astronomical research infrastructures. While we cannot exclude that items such as the amortization of buildings and equipment or the purchase of goods and services that have generally not been quantified in carbon footprint assessments of astronomy institutes so far may yet represent a notable contribution in some cases, we know that their contribution at IRAP is substantially inferior to that of astronomical research infrastructures. We thus conclude that among the contributions that have so far been considered in the literature, space missions and ground-based observatories are the single most important contribution to the carbon footprint of an average astronomer.

Discussion

It is clear from our analysis that the environmental sustainability of astronomical research infrastructures cannot be neglected if our community is seriously committed to reducing its overall carbon footprint. According to ref. 18, the Earth's land and oceans provide a carbon sink of about $16 \text{ GtCO}_2 \text{ yr}^{-1}$ (corrected for emissions from land-use change), corresponding to a per-capita carbon sink of $2 \text{ tCO}_2 \text{ yr}^{-1}$. To reach net-zero GHG emissions, the per-capita emissions need to be reduced to that level. How the burden of emission reductions should be shared across humanity

is a political question, for which consensus needs to be established collectively. Here we take a common global per-capita target, that is, the same emission target for all humans regardless of their nationality or country of residence, as a reasonable basis for initiating discussion. This would imply that an astronomer's footprint (including all their work-related activities, as well as their activities outside of work and lifestyle) must be reduced within the next decades to $2 \text{ tCO}_2 \text{ yr}^{-1}$. In this scenario, emissions of research infrastructures would need to be divided by at least a factor of 20. In the interests of equity, policymakers may instead adopt nation- or region-specific emission targets. For example, to reach net-zero GHG emissions in France, Italy or Spain, consumption-based emissions would need to be reduced by about a factor of five and one could apply the same reduction factor to astronomers based in those countries. Australia, Canada and the United States currently have larger per-capita emissions and in those countries the reduction factors to reach net-zero GHG emissions would be closer to ten. A further proposition under consideration (for example, ref. 19) is that reduction factors should be based on national responsibility for climate breakdown. In this scenario, many countries in the global north would be required to close their research infrastructures, while countries in the global south would retain more capacity to develop new infrastructures. Whatever strategy for reduction factors is ultimately adopted, however, our results indicate that the required reductions will not be minor changes at the margin. Instead, they will fundamentally change how we do astronomy in the future. Astronomy is, of course, not the only scientific domain that heavily relies on research infrastructures and it is likely that similar conclusions will be reached in other research fields.

A necessary first step is that every existing and planned facility should conduct a comprehensive environmental life-cycle assessment and make the results public. The International Astronomical Union (IAU) could, for example, hold a register of all environmental life-cycle assessments, which would constitute a comprehensive database of knowledge for further studies. Funding agencies and space agencies have a critical role in ensuring that such analyses are conducted and published for each facility that they support. For example, based on our emission factors, the James Webb Space Telescope would have a carbon footprint between $310 \text{ ktCO}_2\text{e}$ (mass-based) and $1,223 \text{ ktCO}_2\text{e}$ (cost-based) and for the Square Kilometre Array we estimate the construction footprint to be 312

ktCO₂e and the annual operations footprint to be 18 ktCO₂e yr⁻¹. These figures are comparable with the largest footprint estimates in our study. It is urgent that we consolidate these estimates and implement effective measures to reduce the parts of their carbon footprint over which we still have control.

For existing infrastructures, the analysis should be used to prepare an action plan for how to reduce the footprint over the coming years. The footprint reductions should be monitored and regularly checked against the action plans and the plans should be adapted if needed. One could mimic the scheme of nationally determined contributions that was agreed upon in the 21st Conference of the Parties Paris Agreement and hold a register of all action plans and achievements at IAU that is publicly accessible. While compliance with carbon footprint reductions cannot be enforced on observing facilities, publishing the action plans and achievements would at least guarantee a transparent and open discussion in the community.

For planned infrastructures, the environmental life-cycle assessments should inform the decision about implementation. Abandoning future projects on the basis of their unacceptably high carbon footprint should be an option, but we emphasize that informed decisions of this nature require robust estimates. Having a centralized inventory of environmental life-cycle assessments of all existing infrastructures would allow the community to determine whether there is a margin in the sustainable carbon budget for new infrastructures. In particular, funding agencies and space agencies should include carbon budget limits in their roadmaps for future research infrastructures, assuring their compliance with the boundaries of our planet.

It is questionable whether the required reduction of the carbon footprint of research infrastructures can be reached within the next few decades using the measures described above, in particular if new infrastructures continue to be proposed and developed at the current pace. A possible solution that is often mentioned in the context of carbon footprint reductions is offsetting, yet effective offsetting requires substantial investments that are commensurable with the cost of building an astronomical research infrastructure (Supplementary Information). For existing facilities, the focus must obviously be put on their decarbonization, and if this is not sufficient then we must face the question of which infrastructures should be kept open and which should be shut down.

For planned new facilities, we must recognize that infrastructure investments that are made today lock in their carbon footprint over decades and that replacing fossil fuel for hardware, propellant and electricity production, transport and space launches with renewable energies requires time and investment and probably new technologies that do not yet exist. Global warming is a rate problem: it is the amount of CO₂ we emit each year that is too high relative to the environment's capacity to absorb and to recycle, producing excess atmospheric CO₂ concentrations that heat our planet. Spreading the roughly 35 GtCO₂ that humanity emits every year¹⁸ over a longer period (for example, 3 years) would bring the per-capita footprint down to about 2 tCO₂ yr⁻¹. Making the annual footprint of astronomical research infrastructures of 1,169 ktCO₂e yr⁻¹ compliant with 60 ktCO₂e yr⁻¹, which is the equal-share target for 30,000 astronomers, implies spreading the annual footprint over about 20 years.

We therefore believe that reducing the pace at which we build new astronomical research infrastructures is the only measure that can make our field sustainable in the short run. This does not mean that we must stop developing new observatories or space missions, but we must do so at a (considerably) slower rate. Once the economy is substantially decarbonized, the rate of construction of new research infrastructures could be increased, considering their potential impact on climate change as well as other detrimental effects on the environment, including biodiversity loss, mineral extraction and use of water resources. The good news is that there is no imperative in science that fixes the rate by which new research infrastructures need to be constructed. Today, the rate is determined by our imagination and, ultimately, by money. Tomorrow, it must be determined by sustainability.

Reducing the pace has many side benefits, some of which have already been recognized earlier by the Slow Science movement²⁰: more comprehensive exploitation of data, more time for in-depth science, less publication pressure and more money available to move the already existing infrastructures towards sustainability. The solution is in our hands, the only question is whether the astronomical community will choose to recognize and make use of it.

Methods

Carbon footprint estimation To estimate the carbon footprint of astronomical research infrastructures, we follow the method developed by the French Agency for Ecological Transition (ADEME; <https://www.bilans-ges.ademe.fr/en/accueil>) and the French Association Bilan Carbone (ABC; <https://www.associationbilancarbone.fr>). This method includes the definition of boundaries for the exercise, the collection and analysis of the relevant data and the proposal of an action plan for the reduction of the carbon footprint.

In this method, the carbon footprint of a research infrastructure is defined as an aggregate of all GHG emissions that are generated within the defined boundaries. To enable aggregation of the different gases that cause global warming, GHG emissions are converted into amounts of carbon dioxide equivalents, denoted CO₂e, which take into account the different warming potentials and lifetimes of the various GHGs emitted into the atmosphere. Specifically, the carbon footprint is computed using

$$\text{Carbon footprint} = \sum_i A_i \times EF_i \quad (1)$$

where A_i are called activity data (for example, MWh of electricity consumed, tonnes of concrete poured or M€ of money spent), EF_i are called emission factors (for example, tCO₂e emitted per MWh consumed, tCO₂e emitted per tonne of concrete poured or tCO₂e emitted per M€ of money spent) and the sum is taken over all relevant activities that have been identified within the defined boundaries.

Since activity data for space missions or ground-based observatories are scarce, we will primarily use an EIO analysis, which in our case amounts to using the cost of a space mission, or the cost for construction and operations of a ground-based observatory, as the relevant activity data. For space missions, we cross-check our analysis by adopting a second approach, which uses the satellite payload launch (or wet) mass as activity data. This means that for space missions equation (1) simplifies to

$$\text{Carbon footprint}_{c/m} = A_{c/m} \times EF_{c/m} \quad (2)$$

where $A_{c/m}$ is either mission cost or payload launch mass and $EF_{c/m}$ the corresponding emission factor, while for ground-based observatories we use

$$\text{Carbon footprint} = A_{\text{co}} \times EF_{\text{co}} + A_{\text{op}} \times T \times EF_{\text{op}} \quad (3)$$

where A_{co} is the construction cost, A_{op} the annual operating cost, T the lifetime in years and EF_{co} and EF_{op} are the emission factors for construction and annual operations, respectively. For many activities, emission factors can, for example, be found in ref. 15, yet such databases do not contain specific emission factors for ‘tCO₂e per kg of payload mass’ or ‘tCO₂e per M€ of operating costs’. We therefore estimate dedicated emission factors based on published carbon footprint assessments for astronomical research infrastructures for our analysis (see ‘Emission factors’).

We aim for using activity data and emission factors that cover scopes 1–3 of a carbon footprint assessment, where scope 1 refers to direct emissions from sources owned or controlled by a research infrastructure (that is, any owned or controlled activities that release emissions straight into the atmosphere, such as a gas or diesel generator owned by an observatory), scope 2 refers to indirect emissions from the consumption of purchased electricity, heat, steam or cooling (for example, emissions related to purchased electricity needed for observatory operations) and scope 3 refers to indirect emissions from other activities not directly controlled by the research infrastructure (for example, emissions related to the construction phase of a facility and employee travel). We approach this goal by using emission factors that are based on scope 1–3 analyses, yet we recognized that in some cases the activity data used do not fully cover all scopes and consequently our carbon footprint assessment presents therefore only a lower limit to a full scope 1–3 analysis.

We furthermore aim for a full LCA, covering phase A (feasibility), phase B (preliminary definition), phase C (detailed definition), phase D (qualification and production), phase E (utilization) and phase F (disposal) for space missions and design and definition, construction, operations and dismantling for ground-based observatories. Yet the feasibility and disposal phases are generally excluded from the activity data, which also do not cover the long-term conservation of the acquired data after the end of a space mission. We also note that for space missions, information on mission extension was not always available and consequently the carbon footprint assessment may be

limited to the initial mission definition, which often covers only the first few years of operations. For ground-based observatories the footprint is after a few decades dominated by the operations footprint, however the full operational lifetime of an observatory, and hence its life-cycle footprint, is not known in advance. We therefore decided to limit the operations part of our carbon footprint assessment to the end of our reference year 2019.

As this work was conducted in the context of our institute's effort to estimate its carbon footprint, we considered all space missions and ground-based observatories that were used to produce peer-reviewed journal articles authored or co-authored by IRAP scientists in 2019. To achieve this, we scrutinized the titles and abstracts of all publications signed by authors that were affiliated to IRAP in 2019 using the Astrophysics Data System (ADS) and collected a list of all research infrastructures from which data were used to produce the papers. In a few cases where the usage of research infrastructures was not obvious from the title or abstract of the paper, we also scrutinized the full text of the publication. In total, we identified 46 space missions and 39 ground-based observatories that were used by IRAP scientists to produce peer-reviewed journal articles published in 2019.

Emission factors

Space missions

There exist no publicly available data on the life-cycle carbon footprint of planned or existing space missions, despite the work that has been done in this field for more than a decade or so (for example, by ESA in the context of the Clean Space initiative)²². ESA maintains a comprehensive LCA database yet declined to share it with us for our work. But even if ESA had provided its database, without detailed activity data the database would have been of very limited use for our work.

Nevertheless, ESA has published relative contributions of the life-cycle breakdown for some launchers and space missions, which allows us to perform consistency checks and order-of-magnitude es-

timates. For example, for the Sentinel-3B mission, an Earth observation satellite of the EU Copernicus programme, ref. 23 found that 44% of the carbon footprint is attributable to launcher-related activities, 25% to the operations phase and 19% to the definition, qualification and production of the spacecraft, referred to as phase C+D. In their life-cycle assessment of the Astra-1N and the MetOP-A missions, ref. 24 also find that the launch campaign dominates the carbon footprint (59–64%), followed by phase C+D (27–28%), manufacturing, assembly, integration and test (7–10%) and operations (1–2%). Overall, it is estimated that between 50% to 70% of the carbon footprint of a space mission is related to the launcher production, launch campaign and launch event, depending on the launcher’s dry mass²⁵.

In our work, we will use an estimate for the life-cycle carbon footprint of a space mission that is based on a space-specific life-cycle sustainability assessment (LCSA) framework developed by ref. 16 during his PhD thesis and that he carefully cross-checked with the ESA tools and database. He applied his framework for two case studies: the MÌOS mission, a small satellite mission to the Moon that aimed to collect data on the micrometeorite and radiation environment and detect the presence of water/ice on the lunar south pole in view of a future Moon base, and the NEA-CORE mission, a set of six nanosatellites for the exploration of asteroids by collision and flyby reconnaissance.

In the ref. 16 case study, the MÌOS mission is launched with Ariane 5 ECA together with 3 other missions, hence only 25% of the carbon footprint of the launch segment is attributed to the MÌOS mission. The payload has a wet mass of 286 kg and the assumed mission duration is 2 years. Reference 16 estimated the total carbon footprint of the mission to be 11,200 tCO₂e and a cost of €165 million after applying an inflation correction to convert to 2019 economic conditions, resulting in a monetary emission factor of 68 tCO₂e M€⁻¹ and a per payload wet-mass emission factor of 39 tCO₂e kg⁻¹.

The NEACORE mission is launched with a dedicated PSLV-CA rocket. The 6 nanosatellites have a total wet mass of 143 kg and the assumed mission duration is 4 years and 8 months. Reference 16 estimated the total carbon footprint of the mission to be 8,780 tCO₂e and a cost of €41 mil-

lion when converted to 2019 economic conditions, resulting in a monetary emission factor of 214 tCO₂e M€⁻¹ and a per payload wet-mass emission factor of 61 tCO₂e kg⁻¹.

Taking the mean value of the results from ref. 16 leads to emission factors of 140 tCO₂e M€⁻¹ and 50 tCO₂e kg⁻¹, which are the values that we adopt for our study. We note that the MÌOS and NEACORE estimates differ by less than 53% from these mean values, which is well within the 80% uncertainty that we adopt for individual facilities in our study.

Ground-based observatories

For ground-based observatories, we use monetary emission factors that we estimate separately for construction and operations since the related activities may have different carbon footprint breakdowns. For example, construction often needs important quantities of concrete and steel, with a very high carbon footprint of 1,700–1,800 tCO₂e M€⁻¹, while operations typically consume a lot of electricity, which, for example, in Chile has a typical carbon footprint of 2,500 tCO₂e M€⁻¹ (ref. 15). We did not apply a similar separation in our analysis of space missions, since their operations footprint is estimated to be small compared with their construction footprint^{23,24}.

Construction Reference 26 has estimated the carbon footprint of the Giant Radio Array for Neutrino Detection (GRAND), an experiment that aims to detect ultra-high-energy neutrinos with an array of radio antennas. The ref. 26 carbon footprint estimate for GRAND includes travel, digital technologies and the hardware equipment. For the 3 stages of the project, lasting 25 years in total, the authors obtained a total carbon footprint of 147,220 tCO₂e. The footprint is dominated by the production of stainless steel for the antennas, data storage and data transfer. Excluding the footprint of digital technologies (as it is mostly related to operations and not construction), results in a construction footprint of 81,239 tCO₂e. A construction cost estimate of 200 M€ for the GRAND project has been quoted by ref. 27, excluding the cost of rent and salaries. Using that cost estimate results in a formal monetary emission factor of 406 tCO₂e M€⁻¹ for GRAND construction, which

is a plausible order-of-magnitude estimate that is in close agreement with the monetary emission factor for electrical and information technology equipment ($400 \text{ tCO}_2\text{e M€}^{-1}$)¹⁵.

For the European Extremely Large Telescope (E-ELT), a 39.3-m-diameter optical and near-infrared telescope that is currently under construction in Chile, the European Southern Observatory estimates the construction carbon footprint to be $63.7 \text{ ktCO}_2\text{e}$, covering different quantities of material as well as the energy needed for some parts of the work (for example, blasting, road construction and so on) (ESO, personal communication). Using the E-ELT construction cost of 945 M€ , quoted in the E-ELT construction proposal²⁸ (converted to 2019 economic conditions), results in a monetary emission factor of $67 \text{ tCO}_2\text{e M€}^{-1}$, which is considerably smaller than the GRAND estimate and considerably lower than any sector-based estimate in ref. 15.

Since the E-ELT estimate does not cover all construction activities, the derived emission factor presents what is clearly a lower limit, while with a cost estimate that does not comprise the full project cost, the GRAND estimate presents what is clearly an upper limit to the emission factor. In the absence of more reliable information for the construction-related footprint for ground-based observatories, we take the mean value of $240 \text{ tCO}_2\text{e M€}^{-1}$ of the GRAND and E-ELT estimates and note that the individual estimates are within our adopted uncertainty of 80% of this mean value.

Operations According to ESO (personal communication), the carbon footprint of the Paranal and the La Silla observatories in 2018 were $8.6 \text{ ktCO}_2\text{e yr}^{-1}$ and $2.3 \text{ ktCO}_2\text{e yr}^{-1}$, respectively. Both footprints are dominated by energy use (71% for Paranal, 92% for La Silla), followed by commuting (11% for Paranal, 5% for La Silla) and capital goods (15% for Paranal, 2% for La Silla). Some of the purchases for Paranal and La Silla are accounted for in the carbon footprint estimated by ESO (personal communication) for the Vitacura site and following the recommendation by R. Arsenault (personal communication) we added 30% of the purchase footprint of the Vitacura site to both the Paranal and La Silla footprints, resulting in $9.4 \text{ ktCO}_2\text{e yr}^{-1}$ for Paranal and $2.8 \text{ ktCO}_2\text{e yr}^{-1}$ for La Silla.

The annual operations budget of the Paranal observatory in 2011 has been quoted as 16.9 M€ (18.6

M€ in 2019 economic conditions) plus 174 full-time equivalents (a measurement of workforce employed as equivalent to full-time employees)²⁹. Assuming 120 k€ per full-time equivalent (2019 economic conditions; ref. 30), one can estimate the annual operations budget of Paranal in 2019 to be 39.5 M€, which results in a monetary emission factor of 238 tCO₂e M€⁻¹ for Paranal operations. For La Silla, ref. 31 has quoted an operations budget of 5.9 M€ in 2004 (7.9 M€ in 2019 economic conditions), resulting in a monetary emission factor of 354 tCO₂e M€⁻¹ for La Silla operations.

For the Canada–France–Hawaii Telescope (CFHT), ref. 32 has estimated the 2019 GHG emission of CFHT operations, including travel, the CFHT-owned vehicle fleet and on-site energy consumption. The total carbon footprint for these items amounts to 749 tCO₂e, dominated by power generation (63%) and transportation (31%). For an operations budget of 6.3 M€ for the same year³³, this results in a monetary emission factor of 119 tCO₂e M€⁻¹ for CFHT operations, considerably below the estimate for Paranal and La Silla. The authors note that flight-related emissions may be underestimated in their study and alternative estimators for flight-related emissions¹¹ indeed have yielded an estimate that is higher by a factor of two. Doubling the contribution of flights in the original calculation by ref. 32 would result in a total footprint of 923 tCO₂e and a monetary emission factor of 148 tCO₂e M€⁻¹ for CFHT operations. Additional emission sources such as the purchase of materials or food for employees that were not considered by ref. 32 would further increase this factor.

Based on these 3 estimates, we adopt an average monetary emission factor of 250 tCO₂e M€⁻¹ for observatory operations in our analysis, which is the rounded mean value of the Paranal, La Silla and CFHT estimates. All specific estimates above are well within our adopted 80% uncertainty of this average. We note that the exact value of this factor is strongly dependent on the carbon intensity of the means of electricity production that is used to power the observatory. The same applies to computing and data storage, as well as ground support for space missions. More dedicated life-cycle assessments of specific research infrastructures are needed here to better understand the importance of these contributions to the total carbon footprint.

Adopted emission factors The emission factors that we use throughout this study are summarized in Table 1. For comparison, typical monetary emission factors in France range from 110 tCO₂e M€⁻¹ for insurance and banking, over 400 tCO₂e M€⁻¹ for electrical and optical information technology and office equipment, 700 tCO₂e M€⁻¹ for machinery equipment, up to 1,700 tCO₂e M€⁻¹ for metals and 1,800 tCO₂e M€⁻¹ for mineral products¹⁵. The relatively low monetary emission factor for space missions is related to the fact that space missions are much less material intensive compared with ground-based observatories after normalizing by cost. For example, the liftoff mass of a €1 billion space mission launched with Ariane 5 ECA is about 790 tonnes³⁴, while the E-ELT (which has a similar cost) has a mass of about 60,000 tonnes³⁵. The space sector is in fact unique, and is characterized by low production rates, long development cycles and specialized materials and processes¹⁷.

We also note that the emission factor for ground-based observatory construction is based on rather recent estimates, while some of the observatories that we consider were constructed several decades ago, at a time when the carbon intensity of construction was probably larger. Our construction footprint estimates for the corresponding observatories are therefore likely to be lower limits.

We stress that the values of the emission factors that we adopt remain rather uncertain, given the scarcity of publicly available information relating to life-cycle assessments for astronomical research infrastructures. Reference 15 has quoted a typical uncertainty of 80% for monetary emission factors, which corresponds to the typical scatter of the scarce data about the adopted emission factors in Table 1. This uncertainty clearly dominates the uncertainties of our results. We note, however, that our monetary emission factors are already on the low side of the sector-based estimates in ref. 15, hence it seems unlikely that our adopted values are notably overestimated. The true emission factors and the resulting carbon footprint could easily be larger. More work is needed in this area, and we urge the agencies responsible for existing and future infrastructures for astronomy research, as well their public and industry partners, to contribute actively to consolidating carbon footprint estimates.

Annual footprint To compute the annual carbon footprint of a research infrastructure, we need to devise a method of how to distribute the life-cycle footprint of space missions or the construction footprint of ground-based observatories over the years. For that purpose, we define as the annual carbon footprint the total carbon footprint divided by the number of years over which the greenhouse gases were emitted. The accounting is started with the launch for a space mission or with start of operations for ground-based observatories. For space missions, we divide the lifetime carbon footprint by the lifetime of the mission. For missions that were launched recently, we assume a lifetime of 10 years. In other words, we assume a minimum operations period of 10 years for all infrastructures, avoiding attributing an artificially large annual GHG emission to missions that were launched recently. For ground-based observatories, we divide the construction footprint by the lifetime of the observatory and add the annual operations footprint. For observatories that were built after 2009, we assume a lifetime of at least 10 years, otherwise we take the number of years since first light as the lifetime.

The user community of astronomical research infrastructures To put the carbon footprint results in perspective, we estimated for each research infrastructure the total number of peer-reviewed papers that either analyse data from a given infrastructure or that refer to analysed data from the infrastructure or to the infrastructure itself. We obtained the number of such publications from ADS, using a full-text search over the period from launch until our reference year of 2019. We constructed a dedicated query string for each infrastructure with the aim to cover as many infrastructure-related publications as possible while keeping the false positives at a minimum (the script that we used for this work, including the definition of our query strings, can be accessed at <https://doi.org/10.5281/zenodo.5835840>). We checked the latter by visually investigating a sample of ~ 100 results for each query. We used the same ADS query to assess the number of unique authors that signed at least one of the peer-reviewed papers. While the number of papers can be considered as a measure of the infrastructure impact, the number of unique authors can be considered as a measure of the size of the community that is using the infrastructure.

Carbon intensity Using the above estimates of the user community we can then compute the carbon intensity of a facility, which we define as the lifetime carbon footprint divided by either the number of peer-reviewed papers or the number of unique authors. The meaning of these quantities is that they relate the total carbon footprint of a given infrastructure to the scientific productivity of the community and to the size of the community that makes use of it. The units of the carbon intensity should, however, not lead to the conclusion that writing a paper will actually have the quoted carbon footprint or adding one more author will increase the carbon footprint. While writing a paper has some carbon footprint, we do not estimate its value here as it is not in the scope of this paper and it will be small compared with the per-paper footprint of research infrastructures³⁶. What we estimate is the share of the carbon footprint of a given infrastructure among the scientific community, and writing one more paper or adding one more author will actually reduce the carbon intensity as it will increase the denominator in the equations. This means that the carbon intensity is a dynamic quantity that will evolve with time (Fig. 1).

The worldwide footprint of astronomical facilities The research infrastructures that we selected for this study obviously represent only a subset of all astronomical research infrastructures that exist worldwide and reflect the specific research activities of the scientists at IRAP. We can, however, extrapolate the results to all astronomical research infrastructures to estimate their total carbon footprint globally. For this exercise, we limit ourselves to the research infrastructures that were active in 2019, disregarding the space missions in Table 2 that had stopped operating. We divide all research infrastructures into broad categories that reflect scientific topic (for example, solar, plasma or astro) or observatory type to reduce the bias introduced by the specific selection of infrastructures in Tables 2 and 3. We note that we split optical-near-infrared (OIR) telescopes into facilities with diameter of 3 m or larger and those with smaller diameters since they differ substantially in carbon footprint and in total number. While the total number of telescopes with mirrors of at least 3 m diameter is easy to determine, we only have an approximation for the number of smaller telescopes. For example, ref. 37 provides a directory of about 1,000 professional astronomical observatories and telescopes, while the IAU Minor Planet Center lists 2,297 observatory codes³⁸. We therefore make our estimate by assuming that there exist at least 1,000 professional OIR tele-

scopes worldwide with diameters smaller than 3 m. Due to their vastly different footprints, we also separate single-dish radio telescopes from multiple-dish or antennae arrays. Finally, we also list all other instruments, including the Stratospheric Observatory for Infrared Astronomy (SOFIA), but do not extrapolate this number due to the heterogeneity of the infrastructures in this category.

For each of the categories, we determined the number of active research infrastructures in our list and compared them with the total number of research infrastructures that were active worldwide in 2019. The full list of facilities that we considered is provided in Supplementary Data 1. We then did a bootstrap sampling by randomly selecting N times an infrastructure from the list of active infrastructures in a given category, where N is the total number of research infrastructures that exist worldwide in a given category. We note that a given infrastructure in our list can be sampled several times in this process. Summing the carbon footprints for the N sampled infrastructures then provides an estimate for the total carbon footprint of all infrastructures that exist worldwide. We repeated the random sampling 10,000 times and computed the mean and standard deviations of all estimates to assess the carbon footprint of all infrastructures and the uncertainty that arises from the random sampling procedure. The resulting distribution of carbon footprints is shown in the left panel of Fig. 2.

We reiterate that the results obtained by this method are order-of-magnitude estimates, obtained under the assumption that the research infrastructures in Tables 2 and 3 are representative for all astronomical research infrastructures that exist worldwide. To estimate the sensitivity of our result to this assumption, we repeated the bootstrap procedure by excluding the infrastructure with the largest carbon footprint in each category from the sampling, adding its footprint directly to the result. This avoids sampling infrastructures that are unique in terms of carbon footprint and for which no equivalent exists worldwide, such as, for example, the HST or the ALMA observatory, multiple times. This reduces the carbon footprint estimates and their sampling spread, as illustrated in the right panel of Fig. 2.

The number of astronomers in the world To estimate how much research infrastructures contribute to the annual carbon footprint of an average astronomer, we need to estimate the number

of professional astronomers worldwide. The IAU lists 12,165 members at the beginning of August 2021³⁹, yet not every astronomer is a member of the IAU. Reference 40 studied the fraction of astronomers with PhD degrees who joined IAU for 12 countries (including astronomers, astrophysicists, physicists who study cosmology, high energy astrophysics or astroparticle physics), finding that on average 51% of all astronomers with PhD degrees are members of the IAU. This would imply that there are 24,000 astronomers with PhD degrees worldwide. The country where the fewest astronomers joined the IAU is the United States, with only 40% of astronomers being members of IAU. Applying this fraction would imply that there are 30,000 astronomers with PhD degrees worldwide, which probably is an upper limit. We apply this number in our work to make sure that we do not overestimate the per-astronomer footprint of astronomical research infrastructures.

Data Availability

All data used for this work are available for download at <https://doi.org/10.5281/zenodo.5835840>.

Code Availability

All code used for this work is available for download at <https://doi.org/10.5281/zenodo.5835840>.

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Acronyms Acronyms used throughout this paper represent: Hubble Space Telescope (HST), International Gamma-Ray Astrophysics Laboratory (INTEGRAL), X-ray Multi-Mirror mission (XMM), Rossi X-ray Timing Explorer (RXTE), Solar Dynamics Observatory (SDO), Mars Atmosphere and Volatile Evolution mission (MAVEN), Röntgensatellit (ROSAT), Mars Reconnaissance Orbiter (MRO), Solar and Heliospheric Observatory (SoHO), Astronomy Satellite (AstroSat), Magnetospheric Multiscale mission (MMS), Solar Terrestrial Relations Observatory (STEREO), Advanced Composition Explorer (ACE), Interior Exploration using Seismic Investigations, Geodesy and Heat Transport probe (InSight), Parker Solar Probe (PSP), Wide-field Infrared Survey Explorer (WISE), Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics mission (TIMED), Interplanetary Monitoring Platform 8 (IMP-8), Neutron star Interior Composition Explorer (NICER), Nuclear Spectroscopic Telescope Array (NuSTAR), Transiting Exoplanet Survey Satellite (TESS), Galaxy Evolution Explorer (GALEX), Detection of Electromagnetic Emissions Transmitted from Earthquake Regions satellite (DEMETER), Very Large Telescope array (VLT), Atacama Large Millimeter/submillimeter Array (ALMA), Stratospheric Observatory for Infrared Astronomy

(SOFIA), Anglo-Australian Telescope (AAT), Very Large Array (VLA), Very Long Baseline Array (VLBA), Institut de radioastronomie millimétrique (IRAM), Canada France Hawaii Telescope (CFHT), European Southern Observatory (ESO), Green Bank Telescope (GBT), Low-Frequency Array (LOFAR), James Clerk Maxwell Telescope (JCMT), Australia Telescope Compact Array (ATCA), High Energy Stereoscopic System (H.E.S.S.), More of Karoo Array Telescope (MeerKAT), Gran Telescopio Canarias (GTC), Nobeyama Radio Observatory (NRO), Large Millimeter Telescope (LMT), Mauna Loa Solar Observatory (MLSO), Atacama Pathfinder Experiment (APEX), Submillimeter Array (SMA), Event Horizon Telescope (EHT), Telescope Bernard Lyot (TBL), Observatoire de Haute-Provence (OHP), Korea Microlensing Telescope Network (KMTNet), Télescope Héliographique pour l'Etude du Magnétisme et des Instabilités Solaires (THEMIS), Yunnan Astronomical Observatory (YAO), Himalayan Chandra Telescope (HCT), Fred Lawrence Whipple Observatory (FLWO), National Astronomical Observatory San Pedro Mártir (OAN-SPM), Bohyunsan Optical Astronomy Observatory (BOAO), Optical Gravitational Lensing Experiment (OGLE), Centre Pédagogique Planète Univers (C2PU), Télescope à Action Rapide pour les Objets Transitoires (TAROT), and Nanshan One meter Wide-field Telescope (NOWT).

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Author Contributions Statement J.K. gathered the activity data, made the estimates of the emission factors, estimated the carbon footprints and drafted the paper. All authors defined the analysis method and the IRAP carbon footprint attribution method, elaborated the discussion section and reviewed the manuscript.

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Supplementary Information

Activity data

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 ⁴³. In other cases, the extensions were not included, and in a few cases, the construction cost value quotes we found were suspiciously low.

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 ⁷¹ suggest that

$$\text{Construction cost} = 1.0 \times D^{2.58} \text{ M€} \quad (4)$$

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	41
Chandra	5,860	4,114	42
Cassini	5,820	2,806	43
Cluster	4,800	944	44
Fermi	4,303	863	45
INTEGRAL	4,000	419	46
Curiosity	3,893	2,590	43
XMM	3,800	1,113	47
Juno	3,625	1,082	43
Herschel	3,400	1,152	48
RXTE	3,200	360	49
SDO	3,100	865	50
Rosetta	2,900	1,709	51
Galileo	2,560	1,275	43
MAVEN	2,454	638	43
ROSAT	2,421	635	52
MRO	2,180	928	43
GAIA	2,034	1,037	53
Planck	1,900	775	54
SoHO	1,850	1,469	55
Suzaku	1,706		
AstroSat	1,515	27	57
MMS	1,360	1,054	56
Venus Express	1,270	300	59
WIND	1,250		
STEREO	1,238	614	58
Mars Express	1,223	374	60
Dawn	1,218	439	43
Hipparcos	1,140	933	61
Kepler	1,052	636	62
GEOTAIL	1,009		
Akari	952	106	63
Spitzer	950	1,188	64
SWIFT	843	279	65
ACE	752		
InSight	694	714	43
PSP	685	1,310	41
WISE	661	335	66
TIMED	660	259	65
Double Star	560		
IMP-8	410		
NICER	372	53	67
NuSTAR	360	156	68
TESS	325	275	69
GALEX	280	120	65
DEMETER	130	21	70

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 (M€)	Reference	Operations (M€ yr ⁻¹)	Reference
VLT (Paranal)	1,384	76	40	77
ALMA	1,248	78	105	79
SOFIA	1,098	56	90	56
AAT	124	80	15	81
VLA	345	73	10	82
VLBA	132	83	15	83
IRAM	51	84	15	85
Gemini-South	135	73	13	73
CFHT	85	76	6.3	86
ESO 3.6m (La Silla)	99	87	5.2	87
GBT	120	88	10	89
LOFAR	200	90	9.2	91
JCMT	38	92	5.5	93
ATCA	95	94	3.5	95
H.E.S.S.	49	(1)	8.8	30
MeerKAT	128	96	13	96
GTC	125	76		
NRO	51	(1)	1.5	(1)
LMT	77	97	3.1	98
MLSO			1.2	99
APEX	20	(1)	2.7	100
SMA	60	101		
EHT	52	102	-	-
Noto Radio Observatory			1.5	103
2m TBL	6.0	(2)	1.0	104
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. (4), (3) assuming 10% of construction cost as annual operation costs.

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. ⁷²), 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 ⁷³ 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 ⁷⁴, 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 extrapolated from the values provided by ³⁰ for France and assuming a French contribution of 28% to the project, estimated from the fraction of French authors on the paper ⁷⁵.

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 ktCO₂e (mass-based) to 24 ± 5 ktCO₂e (cost-based) for the space missions and 13 ± 5 ktCO₂e for the ground-based observatories, totalling to 35 ± 7 ktCO₂e 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 ktCO₂e (mass-based and cost-based) for the space missions and 8 ± 3 ktCO₂e for the ground-based observatories, totalling to 20 ± 3 ktCO₂e 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 tCO₂e 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 tCO₂e 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 ktCO₂e (mass-based) and 2.8 ± 0.6 ktCO₂e (cost-based) for the space missions, and 1.3 ± 0.5 ktCO₂e for the ground-based observatories, totalling to 4.0 ± 0.7 ktCO₂e for IRAP in 2019. For each of the IRAP astronomers with PhD degree this corresponds to a footprint of 27.4 ± 4.8 tCO₂e, for each person working at IRAP in 2019, the footprint is 15.0 ± 2.6 tCO₂e. 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 infras-

structures 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 tCO₂e.

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^{105,106}. At the time of writing the paper (September 2021), the EU ETS carbon price was at 61 € per tonne of CO₂¹⁰⁷, which expressed in allowed CO₂ emissions per amount of money spent corresponds to 16,400 tCO₂e M€⁻¹. Individual offsetting projects have prices of the same order of magnitude, for example atmosfair, a popular scheme in Germany, uses 23 € per tonne of CO₂ at the time of writing the paper¹⁰⁸, corresponding to an allowance of 43,500 tCO₂e M€⁻¹. In other words, the allowance to emit CO₂ 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 CO₂ emissions by offsetting is basically zero.

Is it possible to take a given amount of CO₂ 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€¹⁰⁹. Depending on the prior use of the land, transforming agricultural land to forest brings an additional carbon sequestration of 1.6 tCO₂e per hectare and year, replacing a meadow by a forest brings an additional sequestration of 370 kgCO₂e per hectare and year¹⁵. 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 ktCO₂e yr⁻¹ would require planting 70,000 hectares of forest, which would correspond to an investment of 210 M€. Additionally absorbing its construction footprint of 300 ktCO₂e over a decade (the time scale suggested by the IPCC¹ 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 be factored into project costs as early as possible.