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 relate cost and payload mass to carbon footprint. We find that currently worldwide active astronomical research infrastructures have a carbon footprint of 20.3±3.3 Mt CO_2e and an annual emission of 1169±249 kt CO_2e / yr corresponding to a footprint of 36.6±14.0 t CO_2e / yr per astronomer. Compared to 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 International 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 CO_2 and other greenhouse gas emissions occur in the coming decades.” [1]. As stated by António Guterres, UN 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 in the global effort to reduce greenhouse gas (GHG) [3–6]. Much recent attention has focused on the reduction of academic flying [7–11] 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 decade-long lifetime of research infrastructures, decisions that are taken 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 lack, we have developed a method that provides a first order estimate of the carbon footprint of astronomical research infrastructures (see 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, [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 data [14]. 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 analysis [15].

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 emphasise 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 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 then 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 Methods, these reports are currently very scarce. We found two case studies for lifecycle carbon footprints of space missions, which covered the entire mission including the launcher and a few years of operations [16]. From these studies we infer mean emission factors of 140 t CO_2e per M€ of mission cost and 50 t CO_2e per kg 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 t CO_2e / M€ for construction and of 250 t CO_2e / M€ for operations. The emission factors are summarised in Table 1. The lower monetary emission factor for space missions compared to ground-based observatories can be attributed to the low production rates, long development cycles, and specialised materials and processes of the space sector [17].

Table 2 summarises order of magnitude estimates for the carbon lifecycle footprints of space missions based on payload launch mass and mission cost (see Methods and Supplementary Tables 1 and 2). The cost-based estimates are on average about 20% larger than the mass-based estimates, likely 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 may also be due to underestimates of the true costs. For example, INTEGRAL makes use of the same satellite bus as XMM-Newton, which led to important cost savings. On the other hand, the quoted cost estimate for INTEGRAL only covers the mission cost to 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 AstroSat and Akari appear to be significantly 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. The European Space Agency (ESA) advises against using EIO analyses due to their large inherent uncertainties [13], yet our analysis suggests that as long as the uncertainties are properly considered, an EIO analysis for space missions yields results that are comparable to 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 $4.6\pm$

0.8 Mt CO_2e for the mass-based and 5.9 ± 1.2 Mt CO_2e 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 Mt CO_2e. Assuming that the same increase would apply to the remaining six space missions for which we did not find any cost estimates would lead to a cost-based estimate of 6.2 ± 1.3 Mt CO_2e. Table 2 also lists the annual footprints of the facilities, computed by dividing the lifecycle footprints by the lifetime of the mission, defined as the time since launch or ten years, whichever is longer (see Methods). The total annual footprint of the missions in Table 2 is 310 ± 47 kt CO_2e / yr for the mass-based and 366 ± 64 kt CO_2e / yr for the cost-based estimates.

Order of magnitude estimates for the carbon lifecycle footprints of ground-based observatories are summarised in Table 3. After a few decades, the operations footprint dominates the lifecycle footprint. The lifecycle carbon footprint of the ground-based observatories listed in Table 3 is estimated to be 3.0 ± 0.8 Mt CO_2e, with a total footprint for construction of 1.4 ± 0.4 Mt CO_2e (46%) and for operations of 1.6 ± 0.4 Mt CO_2e (54%). The total annual carbon footprint amounts to 194 ± 64 kt CO_2e / yr 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 Methods). The significance 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 facilities still have a significant carbon intensity decades after their launch or start of operations. Since the distribution of carbon intensities among the facilities is obviously heavily

Table 1: Adopted emission factors.

Activity	Emission factor
Space missions (per payload launch mass)	50 t CO_2e / kg
Space missions (per mission full cost)	140 t CO_2e / M€
Ground-based observatory construction	240 t CO_2e / M€
Ground-based operations	250 t CO_2e / M€

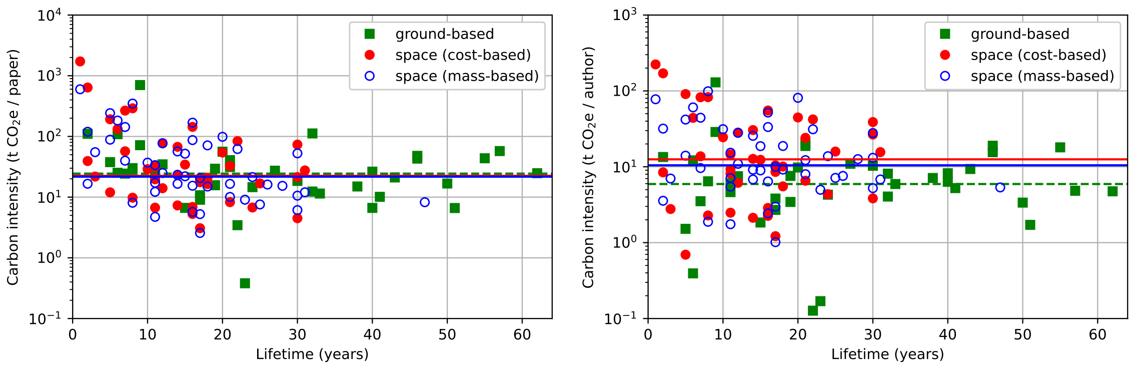

Figure 1: Carbon intensity versus time since launch or start of operations for space missions (open blue circles for mass-based and filled red circles for cost-based estimates) and ground-based observatories (green squares). The left panel shows the carbon intensity per peer-reviewed paper, the right panel shows the carbon intensity per unique author. The lines indicates 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. The annual footprints were computed by dividing the lifecycle footprints by the lifetime of the mission, defined as the time since launch or ten years, whatever is longer. The number of peer-reviewed papers and unique authors that signed these papers are indicated for each infrastructure in columns 3 and 4. Using these numbers the carbon intensities (columns 7–8 and 11-12) were computed according to Methods. For cells that are blank no cost estimates could be found.

Mission	Years	Papers	Authors	Mass-based				Cost-based			
		since launch		Footprint	Annual	Carbon intensity		Footprint	Annual	Carbon intensity	
				(t CO_2e)	$\left(\frac{\text{t } CO_2\text{e}}{\text{yr}}\right)$	$\left(\frac{\text{t } CO_2\text{e}}{\text{paper}}\right)$	$\left(\frac{\text{t } CO_2\text{e}}{\text{author}}\right)$	(t CO_2e)	$\left(\frac{\text{t } CO_2\text{e}}{\text{yr}}\right)$	$\left(\frac{\text{t } CO_2\text{e}}{\text{paper}}\right)$	$\left(\frac{\text{t } CO_2\text{e}}{\text{author}}\right)$
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. The lifetime footprint was computed by adding the construction footprint to the annual operations footprint multiplied by the lifetime of the observatory. The annual footprint was computed by dividing the construction footprint by the lifetime of the observatory, defined as the time since first light or ten years (whatever is longer), and adding the annual operations footprint. The number of peer-reviewed papers and unique authors that signed these papers are indicated for each infrastructure in columns 3 and 4. Using these numbers the carbon intensities (columns 9-10) were computed according to Methods. For cells that are blank no cost estimates could be found.

Observatory	Lifetime	Papers	Authors	Footprint				Carbon intensity	
				Construction	Operation	Lifetime	Annual		
	(yr)			(t CO_2e)	$\left(\frac{\text{t } CO_2\text{e}}{\text{yr}}\right)$	(t CO_2e)	$\left(\frac{\text{t } CO_2\text{e}}{\text{yr}}\right)$	$\left(\frac{\text{t } CO_2\text{e}}{\text{paper}}\right)$	$\left(\frac{\text{t } CO_2\text{e}}{\text{author}}\right)$
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

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 t CO_2e / paper for both the mass-based and cost-based estimates. Ground-based observatories have a comparable median carbon intensity of 24 t CO_2e / paper. When normalised by author, space missions have a median carbon intensity of 10 t CO_2e / author for the mass-based and 13 t CO_2e / author for the cost-based estimates, while ground-based observatories have a median value of 6 t CO_2e / author. This suggests that, on average, more authors are involved in publications citing ground-based observatories compared to 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 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, 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 t CO_2e, while for each of the 263 persons working at IRAP in 2019 (i.e. including students and all technical and administrative staff) the footprint is 15.0 ± 2.6 t CO_2e. 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 t CO_2e per IRAP astronomer in 2019 (see 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 Methods). While this method assumes that the research infrastructures considered in this paper are representative for all astronomical facilities that exist worldwide, we reduce the bias introduced by the specific selection by dividing all research infrastructures into broad categories that reflect science topic or observatory type. The results of this exercise are summarised 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 have a total carbon footprint of 7.4 ± 2.2 Mt CO_2e and an annual footprint of 525 ± 184 kt CO_2e / yr, where the uncertainties include the difference between the mass- and cost-based estimates. We note that roughly half of the existing space missions are actually 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 Mt CO_2e and their annual footprint to be 757 ± 131 kt CO_2e / yr. 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 average, longer lifetimes for ground-based observatories compared to space missions.

Summing both contributions yields a total carbon footprint of all active astronomical research infrastructures in 2019 of 21.6 ± 3.2 Mt CO_2e and an annual footprint of 1283 ± 232 kt CO_2e / yr, 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 Methods), we obtain an annual footprint of 42.8 ± 7.7 t CO_2e / yr 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 for 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 Hubble Space Telescope or ALMA, results in a reduced total carbon footprint of 19.1 ± 2.3 Mt CO_2e and annual carbon footprints of 1054 ± 138 kt CO_2e / yr

Table 4: Extrapolated carbon footprint of all active astronomical research infrastructures in the world (see Methods). 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	RIs		Carbon footprint of selected RIs		Carbon footprint of all RIs	
	selected	worldwide	Lifecycle (kt CO_2e)	Annual (kt CO_2e / yr)	Lifecycle (kt CO_2e)	Annual (kt CO_2e / yr)
			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

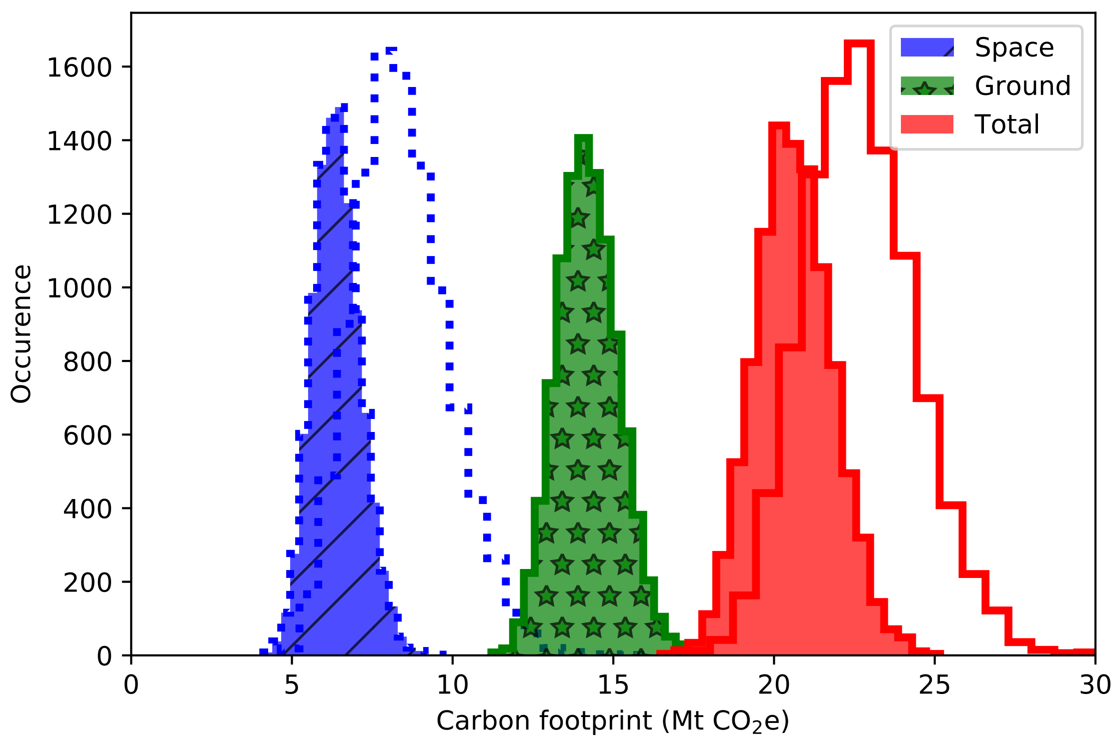

Figure 2: Distribution of the carbon footprint of astronomical research infrastructure that exist worldwide as derived using the bootstrap method. The left figure is for the sampling of all facilities, for the right figure the infrastructure with the largest carbon footprint in each category was excluded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

and 35.1 ± 4.6 t CO_2e / yr 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 Mt CO_2e and an annual carbon footprint of 1169 ± 249 kt CO_2e / yr and 39.0 ± 8.3 t CO_2e / yr 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 t CO_2e / yr, 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 t CO_2e / yr may miss the attribution of the carbon footprint of some infrastructures that were not considered in this paper, the global extrapolation of 42.8 ± 7.7 t CO_2e / yr 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 ± 14.0 t CO_2e / yr per astronomer for research infrastructures to 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, [12] estimated the average carbon footprint of an astronomer at the Max Planck Institut for Astronomy in Heidelberg to be 18.1 t CO_2e / yr, dominated by 8.5 t CO_2e / yr from flights, 5.2 t CO_2e / yr from electricity use, and 3.0 t CO_2e / yr from heating. For the average Australian astronomer (including PhD students), [6] estimated a footprint of at least ≥ 37 t CO_2e / yr, comprised of 22 t CO_2e / yr for supercomputing, 6 t CO_2e / yr from flights, 4 t CO_2e / yr for powering the office buildings and 5 t CO_2e / yr 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 amortisation of buildings and equipment, or the purchase of goods and services that have generally not been quantified in carbon footprint assessments of astronomy institutes to date may yet represent a significant contribution in some cases, we know that their contribution at IRAP is significantly 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 [18], the Earth's land and oceans provide a carbon sink of about 16 Gt CO_2 per year (corrected for emissions from land-use change), corresponding to a per-capita carbon sink of 2 t CO_2 per year. 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, i.e. 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 t CO_2 per year. 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 5, 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 10. A further proposition under consideration, e.g. [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 lifecycle analysis and make the results public. The International Astronomical Union (IAU) could, for example, hold a register of all environmental lifecycle analyses, 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 kt CO_2e (mass-based) and 1223 kt CO_2e (cost-based), and for SKA we estimate the construction footprint to be 312 kt CO_2e and the annual operations footprint to be 18 kt CO_2e / yr. These figures are comparable to the largest footprint estimates in our study. It is urgent to consolidate these estimates, and to 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 Paris COP21 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 lifecycle analysis should inform the decision about implementation. Abandoning future projects on the basis of their unacceptably high carbon footprint should be an option, but we emphasise that informed decisions of this nature require robust estimates. Having a centralised inventory of environmental lifecycle analyses 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 (see Supplementary Information). For existing facilities, the focus must obviously be put on their decarbonisation, and if this is not sufficient, we must face the question of which infrastructures should be kept open and which should be shut down.

For planned new facilities, we must recognise that infrastructure investments that are made today lock in their carbon footprint over decades, and replacing fossil fuel for hardware, propellant and electricity production, transport, and space launches by renewable energies requires time and investment, and likely new technologies that do not yet exist. Global warming is a rate problem: it is the amount of CO_2 we emit each year that is too high relative to the environment's capacity to absorb and to recycle, producing excess atmospheric CO_2 concentrations that heat our planet. Spreading the roughly 35 Gt CO_2 that humanity emits every year [18] over a longer period, for example 3 years, would bring the per-capita footprint down to about 2 t CO_2 per year. Making the annual footprint of astronomical research infrastructures of 1169 kt CO_2e / yr compliant with 60 kt CO_2e / yr, 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 with 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 (significantly) slower rate. Once the economy is substantially decarbonised, 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 recognised earlier by the *Slow Science* movement [20]: 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 recognise 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; see `https://www.bilans-ges.ademe.fr/en/accueil`) and the French Association Bilan Carbone (ABC; see `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 CO_2e, 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

$$\text{Carbon footprint} = \sum_i A_i \times EF_i \tag{1}$$

where A_i are called *activity data* (e.g. MWh of electricity consumed, tonnes of concrete poured, M€ of money spent), EF_i are called *emission factors* (e.g. t CO_2e emitted per MWh consumed, t CO_2e emitted per tonne of concrete poured, t CO_2e 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 economic input-output (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 Eq. (1) simplifies to

$$\text{Carbon footprint}_{\rm c/m} = A_{\rm c/m} \times EF_{\rm c/m} \tag{2}$$

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

$$\text{Carbon footprint} = A_{\rm co} \times EF_{\rm co} + A_{\rm op} \times T \times EF_{\rm op} \tag{3}$$

where $A_{\rm co}$ is the construction cost, $A_{\rm op}$ the annual operating cost, T the lifetime in years, and $EF_{\rm co}$ and $EF_{\rm op}$ are the emission factors for construction and annual operations, respectively. For many activities, emission factors can for example be found in [15], yet such databases do not contain specific emission factors for "t CO_2e per kg of payload mass" or "t CO_2e per M€ operating costs". We therefore estimate dedicated emission factors based on published carbon footprint assessments for astronomical research infrastructures for our analysis (see Methods).

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 (i.e. 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 (e.g. 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 (e.g. 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 recognised that in some cases the activity data used do no 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 lifecycle analysis (LCA), covering phase A (feasibility), phase B (preliminary definition), phase C (detailed definition), phase D (qualification and production), phase E (utilisation) 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 lifecycle 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 scrutinised 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 scrutinised 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 lifecycle carbon footprint of planned or existing space missions, despite the work that is done in this field for more than a decade or so (for example by ESA in the context of the Clean Space initiative) [21]. ESA disposes of a comprehensive Life Cycle Analysis (LCA) database, yet declined to share this database with us for our work. But even if ESA would have 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 lifecycle breakdown for some launchers and space missions, which allows to perform consistency checks and order of magnitude estimates. For example, for the Sentinel-3B mission, an Earth observation satellite of the EU Copernicus program, [22] find that 44% of the carbon footprint is related 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 lifecycle assessment of the Astra-1N and the MetOP-A missions, [23] 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 mass [24].

In our work, we will use an estimate for the lifecycle carbon footprint of a space mission that is based on a space-specific Life Cycle Sustainability Assessment (LCSA) framework developed by [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 aims 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 [16] case study, the MÌOS mission is launched with Ariane 5 ECA together with three 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. [16] estimated the total carbon footprint of the mission to be 11 200 t CO_2e and a cost of 165 M€ after applying an inflation correction to convert to 2019 economic conditions, resulting in a monetary emission factor of 68 t CO_2e / M€ and a per payload wet-mass emission factor of 39 t CO_2e / kg.

The NEACORE mission is launched with a dedicated PSLV-CA rocket. The six nanosatellites have a total wet-mass of 143 kg, the assumed mission duration is 4 years and 8 months. [16] estimated the total carbon footprint of the mission to be 8 780 t CO_2e and a cost of 41 M€ when converted to 2019 economic conditions, resulting in a monetary emission factor of 214 t CO_2e / M€ and a per payload wet-mass emission factor of 61 t CO_2e / kg.

Taking the mean value of the results from [16] leads to emission factors of 140 t CO_2e / M€ and 50 t CO_2e / kg, 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 significant quantities of concrete and steel, with a very high carbon footprint of 1 700 − 1 800 t CO_2e / M€, while operations typically consume a lot of electricity, which for example in Chile has a typical carbon footprint of 2 500 t CO_2e / M€ [15]. We did not apply a similar separation in our analysis of space missions, since their operations footprint is estimated to be small compared to their construction footprint [22,23].

Construction [25] 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 [25] carbon footprint estimate for GRAND includes travel, digital technologies and the hardware equipment. For the three stages of the project, lasting for 25 years in total, the authors obtained a total carbon footprint of 147 220 t CO_2e. The footprint is dominated by the production of stainless steel for the antennas, data storage and data transfer. Excluding the footprint of digital technologies (since it is mostly related to operations and not construction), results in a construction footprint of 81 239 t CO_2e. A construction cost estimate of 200 M€ for the GRAND project is quoted by [26], excluding the cost of rent and salaries. Using that cost estimate results in a formal monetary emission factor of 406 t CO_2e / M€ for GRAND construction, which is a plausible order of magnitude estimate that is in close agreement with the monetary emission factor for electrical and IT equipment (400 t CO_2e / M€) [15].

For the European Extremely Large Telescope (E-ELT), a 39.3 metre diameter optical and near-infrared telescope that is currently under construction in Chile, the European Southern Observatory (ESO) estimates the construction carbon footprint to be 63.7 kt CO_2e, covering different quantities of material as well as the energy needed for some parts of the work (e.g. blasting, road construction...) [27]. Using the E-ELT construction cost of 945 M€, quoted in the E-ELT construction proposal [30] (converted to 2019 economic conditions), results in a monetary emission factor of 67 t CO_2e / M€, which is considerably smaller than the GRAND estimate, and considerably lower than any sector-based estimate in [15].

Since the E-ELT estimate does not cover all construction activities, the derived emission factor presents clearly a lower limit, while with a cost estimate that does not comprise the full project cost, the GRAND estimate presents 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 t CO_2e / M€ 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 [27], the carbon footprint of the Paranal and the La Silla observatories in 2018 were 8.6 kt CO_2e / yr and 2.3 kt CO_2e / yr, 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 [27] for the Vitacura site, and following the recommendation by [28] we added 30% of the purchase footprint of the Vitacura site to both the Paranal and La Silla footprints, resulting in 9.4 kt CO_2e / yr for Paranal and 2.8 kt CO_2e / yr for La Silla.

The annual operations budget of the Paranal observatory in 2011 is quoted as 16.9 M€ (18.6 M€ in 2019 economic conditions) plus 174 Full Time Equivalents (FTEs; a measurement of workforce employed as equivalent to full-time employees) [31]. Assuming 120 k€/FTE (2019 economic conditions; [32]), 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 t CO_2e / M€ for Paranal operations. For La Silla [29] quote an operations budget of 5.9 M€ in 2004 (7.9 M€ in 2019 economic conditions), resulting in a monetary emission factor of 354 t CO_2e / M€ for La Silla operations.

For the Canada France Hawaii Telescope (CFHT), [33] 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 t CO_2e, dominated by power generation (63%) and transportation (31%). For an operations budget of 6.3 M€ for the same year [34], this results in a monetary emission factor of 119 t CO_2e / M€ for CFHT operations, significantly 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 emissions [11] indeed yield an estimate that is higher by a factor of two. Doubling the contribution of flights in the original calculation by [33] would result in a total footprint of 923 t CO_2e and a monetary emission factor of 148 t CO_2e / M€ for CFHT operations. Additional emission sources such as the purchase of material or food for employees that were not considered by [33] would further increase this factor.

Based on these three estimates, we adopt an average monetary emission factor of 250 t CO_2e / M€

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 lifecycle analyses 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 summarised in Table 1. For comparison, typical monetary emission factors in France range from 110 t CO_2e / M€ for insurance and banking, over 400 t CO_2e / M€ for electrical and optical IT and office equipment, 700 t CO_2e / M€ for machinery equipment, up to 1 700 t CO_2e / M€ for metals and 1 800 t CO_2e / M€ for mineral products [15]. The relatively low monetary emission factor for space missions is related to the fact that space missions are much less material intensive compared to ground-based observatories after normalising by cost. For example, the liftoff mass of a one billion euro space mission launched with Ariane 5 ECA is about 790 tonnes [35] while the E-ELT (which has a similar cost) has a mass of about 60 000 tonnes [36]. The space sector is in fact unique, and is characterised by low production rates, long development cycles, and specialised materials and processes [17].

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 likely 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 lifecycle analyses for astronomical research infrastructures. [15] quotes 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 [15], hence it seems unlikely that our adopted values are significantly 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 consolidate 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 lifecycle 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 that missions that were launched recently get attributed an artificially large annual GHG emission. 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 from `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 also 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 significance 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 actually has some carbon footprint, we do not estimate its value here as it is not in the scope of this paper, and it will anyway be small compared to the per-paper footprint of research infrastructures [37]. 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 (see 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 in order 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 science topic (e.g. solar, plasma, 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 metre or larger and those with smaller diameters since they differ significantly in carbon footprint and in total number. While the total number of telescopes with mirrors of at least 3 metre diameter is easy to determine, we only have an approximation for the number of smaller telescopes. For example, [38] provides a directory of about 1 000 professional astronomical observatories and telescopes, while the IAU minor planet centre lists 2 297 observatory codes [39]. We therefore make our estimate by assuming that there exist at least 1 000 professional OIR telescopes worldwide with diameters smaller than 3 metres. 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 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 to the total number of research infrastructures that were active worldwide in 2019. 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`. 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 that infrastructures that are unique in terms of carbon footprint and for which no equivalent exists worldwide, such as for example the Hubble Space Telescope or the ALMA observatory, are sampled 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 2021 [40], yet not every astronomer is a member of the IAU. [41] 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 U.S. 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).

Acknowledgements We thank the referees Robin Arsenault and Lewis Ball as well as a third anonymous referee for their valuable comments. Special thanks go to Robin Arsenault for the insights that he provided on the carbon footprint estimates of ESO infrastructures and sites. We furthermore thank Mathieu de Naurois, Carlos Duran, Zhou Fan, Chung-Uk Lee, Alain Klotz, Kumiko Kotera, Ken Tatematsu, and Simon O'Toole for having provided data that were useful for this research. In addition we thank Nicolas

Flagey, Laurent Pagani, Guobao Song, Madeleine Smith-Spanier, and Andrew Ross Wilson for useful discussions and Kelly Lockhart and Sergi Blanco-Cuaresma for their help with ADS. This research has made use of NASA's Astrophysics Data System Bibliographic Services. In addition, this work has made use of the Python 2D plotting library matplotlib [42].

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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Competing Interests The authors declare no competing interests.

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 [45]. 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 [73] suggest that

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

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	43
Chandra	5 860	4 114	44
Cassini	5 820	2 806	45
Cluster	4 800	944	46
Fermi	4 303	863	47
INTEGRAL	4 000	419	48
Curiosity	3 893	2 590	45
XMM	3 800	1 113	49
Juno	3 625	1 082	45
Herschel	3 400	1 152	50
RXTE	3 200	360	51
SDO	3 100	865	52
Rosetta	2 900	1 709	53
Galileo	2 560	1 275	45
MAVEN	2 454	638	45
ROSAT	2 421	635	54
MRO	2 180	928	45
GAIA	2 034	1 037	55
Planck	1 900	775	56
SoHO	1 850	1 469	57
Suzaku	1 706		
AstroSat	1 515	27	59
MMS	1 360	1 054	58
Venus Express	1 270	300	61
WIND	1 250		
STEREO	1 238	614	60
Mars Express	1 223	374	62
Dawn	1 218	439	45
Hipparcos	1 140	933	63
Kepler	1 052	636	64
GEOTAIL	1 009		
Akari	952	106	65
Spitzer	950	1 188	66
SWIFT	843	279	67
ACE	752		
InSight	694	714	45
PSP	685	1 310	43
WISE	661	335	68
TIMED	660	259	67
Double Star	560		
IMP-8	410		
NICER	372	53	69
NuSTAR	360	156	70
TESS	325	275	71
GALEX	280	120	67
DEMETER	130	21	72

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	78	40	79
ALMA	1 248	80	105	81
SOFIA	1 098	58	90	58
AAT	124	82	15	83
VLA	345	75	10	84
VLBA	132	85	15	85
IRAM	51	86	15	87
Gemini-South	135	75	13	75
CFHT	85	78	6.3	88
ESO 3.6m (La Silla)	99	89	5.2	89
GBT	120	90	10	91
LOFAR	200	92	9.2	93
JCMT	38	94	5.5	95
ATCA	95	96	3.5	97
H.E.S.S.	49	(1)	8.8	32
MeerKAT	128	98	13	98
GTC	125	78		
NRO	51	(1)	1.5	(1)
LMT	77	99	3.1	100
MLSO			1.2	101
APEX	20	(1)	2.7	102
SMA	60	103		
EHT	52	104	-	-
Noto Radio Observatory			1.5	105
2m TBL	6.0	(2)	1.0	106
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. [74]), 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 [75] 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 [76], 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 [32] for France and assuming a French contribution of 28% to the project, estimated from the fraction of French authors on the paper [77].

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.

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 [107,108]. At the time of writing the paper (September 2021), the EU ETS carbon price was at 61 € per tonne of CO_2 [109], 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 [110], 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€ [111]. 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 [15]. 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 [1] 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.