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". As stated by António Guterres, United Nations Secretary-General, the IPCC Sixth Assessment Report is a "code red for humanity".

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). Much recent attention has focused on the reduction of academic flying and, to a lesser extent, on the use of supercomputers. 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 data. 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.

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, the carbon footprint of individual projects at IRAP has been estimated using EIO analysis. We present here results and their uncertainties for astronomical research infrastructures of a few of our institute’s projects.

Using the results from these studies, along with carbon footprint assessments of other astronomical research and development projects, we can derive a first-order estimate of the carbon footprint of the worldwide active astronomical research infrastructures. We have found that research infrastructures make the single largest contribution to the carbon footprint of an astronomer. 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. 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.

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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 operations. 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 tCO₂e M€⁻¹ for construction and of 250 tCO₂e M€⁻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 sector.

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 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 for 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 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 for due to their large inherent uncertainties, 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 a 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 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 tCO₂e

| Table 1 | Adopted emission factors |
|---------|---------------------------|
| Activity | Emission factor          |
| Space missions (per payload launch mass) | 50 tCO₂e kg⁻¹ |
| Space missions (per mission full cost) | 140 tCO₂e M€⁻¹ |
| Ground-based observatory construction | 240 tCO₂e M€⁻¹ |
| Ground-based operations | 250 tCO₂e M€⁻¹ |
| Mission | Years (total since launch) | Footprint (tCO₂e) | Annual (tCO₂e yr⁻¹) | Mass-based Carbon intensity (tCO₂e per paper) | Cost-based Carbon intensity (tCO₂e per author) |
|---------|--------------------------|------------------|---------------------|---------------------------------------------|----------------------------------------------|
| HST     | 30                       | 52,497           | 555,500             | 18,517                                      | 1,125,197                                    |
| Chandra | 21                       | 17,714           | 293,000             | 13,952                                      | 575,955                                      |
| Cassini | 22                       | 4,691            | 291,000             | 13,227                                      | 392,902                                      |
| Cluster | 20                       | 2,433            | 240,000             | 12,000                                      | 132,207                                      |
| Fermi   | 12                       | 8,619            | 215,150             | 19,929                                      | 120,881                                      |
| INTEGRAL| 18                       | 2,808            | 200,000             | 11,111                                      | 58,720                                       |
| Curiosity| 7                        | 1,360            | 194,650             | 143                                          | 362,595                                      |
| XMM     | 21                       | 18,859           | 190,000             | 108                                          | 155,845                                      |
| Juno    | 8                        | 521              | 181,250             | 138                                          | 151,547                                      |
| Herschel| 11                       | 5,046            | 170,000             | 155                                          | 161,238                                      |
| RXTE    | 24                       | 7,473            | 160,000             | 114                                          | 50,438                                       |
| SDO     | 10                       | 4,189            | 155,000             | 111                                          | 121,164                                      |
| Rosetta| 16                       | 1,665            | 145,000             | 87                                           | 239,316                                      |
| Galileo | 30                       | 2,432            | 128,000             | 53                                           | 178,503                                      |
| MAVEN   | 6                        | 672              | 122,700             | 183                                          | 89,270                                       |
| ROSAT   | 30                       | 19,765           | 121,050             | 183                                          | 147,501                                      |
| MRO     | 14                       | 1,927            | 109,000             | 57                                           | 129,850                                      |
| Gaia    | 7                        | 2,550            | 101,700             | 49                                           | 145,114                                      |
| Planck  | 11                       | 5,515            | 95,000              | 17                                           | 108,486                                      |
| SoHO    | 25                       | 12,218           | 92,500              | 12                                           | 205,617                                      |
| Suzaku  | 15                       | 3,869            | 85,300              | 22                                           | 52,332                                       |
| AstroSat| 5                        | 313              | 75,750              | 242                                          | 3,751                                        |
| MMS     | 5                        | 769              | 68,000              | 88                                           | 147,501                                      |
| Venus Express | 15                 | 1,221            | 63,500              | 52                                           | 41,945                                       |
| Wind    | 26                       | 3,877            | 62,500              | 16                                           | 104,868                                      |
| STEREO  | 14                       | 3,731            | 61,900              | 17                                           | 86,021                                       |
| Mars Express | 17                | 2,969            | 61,150              | 21                                           | 52,332                                       |
| Dawn    | 12                       | 791              | 60,885              | 51                                           | 61,409                                       |
| Hipparcos| 31                      | 4,743            | 57,000              | 18                                           | 130,664                                      |
| Kepler  | 11                       | 4,306            | 52,620              | 12                                           | 89,037                                       |
| Geotail | 28                       | 3,288            | 50,450              | 15                                           | 166,333                                      |
| Akari   | 14                       | 2,037            | 47,600              | 23                                           | 36,196                                       |
| Spitzer | 17                       | 9,050            | 47,500              | 5                                            | 14,878                                       |
| Swift   | 16                       | 7,397            | 42,150              | 6                                            | 39,030                                       |
| ACE     | 23                       | 4,147            | 37,600              | 9                                            | 52,332                                       |
| InSight | 1                        | 58               | 34,700              | 598                                          | 99,922                                       |
| PSP     | 2                        | 287              | 34,250              | 398                                          | 183,456                                      |
| WISE    | 11                       | 6,990            | 33,050              | 305                                          | 46,855                                       |
| TIMED   | 18                       | 2,205            | 33,000              | 15                                           | 36,196                                       |
| Double Star| 16                   | 166              | 28,000              | 169                                          | 148,788                                      |
| IMP-8   | 47                       | 2,485            | 20,500              | 436                                          | 2,439                                        |
| NERSTAR | 3                        | 338              | 18,600              | 55                                           | 7                                           |
| NuSTAR  | 8                        | 2,227            | 18,000              | 180                                          | 2,180                                        |
| TESS    | 2                        | 978              | 16,250              | 162                                          | 38,478                                       |
| GALEX   | 17                       | 5,452            | 14,000              | 824                                          | 16,780                                       |
| DEMETER | 16                       | 422              | 6,500               | 406                                          | 2,907                                        |

*Mission acronyms represent: 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), 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 B (IMP-8), Neutron star Interior Composition Explorer (NICER), Nuclear Spectroscopic Telescope Array (NuSTAR), Transiting Exoplanet Survey Satellite (TESS), Galaxy Evolution Explorer (GALEX) and Detection of Electromagnetic Emissions Transmitted from Earthquake Regions satellite (DEMETER).

For cells that are blank, no cost estimates could be found.
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

| Observatory | Lifetime (yr) | Papers | Authors | Construction (tCO₂e) | Operation (tCO₂e yr⁻¹) | Lifetime (tCO₂e) | Annual (tCO₂e yr⁻¹) | Footprint (tCO₂e per paper) | Carbon intensity (tCO₂e 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 | 203,610 | 4,471 | 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 | 464,919 | 48,729 | 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 3.6 m (La Silla) | 43 | 3,774 | 8,515 | 12,233 | 378 | 26,609 | 700 | 15 | 7 |
| GBT | 19 | 2,554 | 9,905 | 28,812 | 2,436 | 75,088 | 5,094 | 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 | 4,018 | 12,537 | 22,863 | 3,190 | 75,088 | 5,094 | 29 | 8 |
| H.E.S.S. | 17 | 4,577 | 12,889 | 11,848 | 2,193 | 49,126 | 3,952 | 29 | 8 |
| MeerKAT | 2 | 335 | 2,750 | 30,624 | 3,190 | 37,004 | 6,252 | 110 | 13 |
| GTC | 11 | 1,059 | 6,445 | 29,880 | 3,190 | 97,280 | 4,864 | 56 | 10 |
| 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 | 119 | 25 |
| MLSO | 55 | 385 | 932 | 30,624 | 3,190 | 124,740 | 4,158 | 18 | 10 |
| APEX | 15 | 2,244 | 8,079 | 4,800 | 675 | 14,925 | 995 | 7 | 2 |
| SMA | 17 | 1,585 | 5,312 | 14,354 | 844 | 29,880 | 1,642 | 11 | 6 |
| EHT | 11 | 606 | 2,079 | 12,580 | 1,144 | 12,580 | 1,144 | 21 | 6 |
| Noto Radio Observatory | 32 | 108 | 1,490 | 378 | 12,096 | 378 | 112 | 0.8 |
| 2 m TBL | 40 | 435 | 1,392 | 1,435 | 250 | 11,435 | 286 | 26 | 8 |
| 2.16 m (Xinglong Station) | 46 | 235 | 651 | 1,750 | 182 | 10,137 | 220 | 43 | 16 |
| 1.93 m 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 |
| 2.4 m LiJiang (YAO) | 12 | 149 | 688 | 2,297 | 239 | 5,168 | 431 | 35 | 8 |
| 2 m HCT | 19 | 276 | 1,259 | 1,454 | 151 | 4,331 | 228 | 16 | 3 |
| 1.5 m Tillinghast (FLWO) | 51 | 652 | 2,514 | 683 | 71 | 4,312 | 85 | 7 | 2 |
| 1.5 m (OAN-SPM) | 50 | 253 | 1,258 | 683 | 71 | 4,241 | 85 | 17 | 3 |
| 1.8 m (BOAO) | 24 | 262 | 892 | 1,093 | 114 | 3,827 | 159 | 15 | 4 |
| 1 m (Pic-du-Midi) | 57 | 29 | 345 | 240 | 25 | 1,665 | 29 | 57 | 5 |
| 1.3 m 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 |
| 1 m NOWT | 7 | 17 | 118 | 240 | 25 | 415 | 49 | 24 | 4 |

*Observatory acronyms represent: Very Large Telescope array (VL T), Anglo-Australian Telescope (AAT), Very Large Array (VLA), Very Long Baseline Array (VLBA), Institut de radioastronomie millimétrique (IRAM), 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 Kanoo Array Telescope (MeerKAT), Gran Telescopio Canarias (GTC), Nobeyama Radio Observatory (NRO), Large Millimeter Telescope (LMT), Mauna Lea 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’Étude 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 Planéte Univers (C2PU), Télescope à Action Rapide pour les Objets Transitoires (TAROT) and Nanshan One-meter Wide-field Telescope (NOWT). The lifetime footprint was computed by adding the construction footprint to the annual operations footprint multiplied by the lifetime of the observatory. For the Event Horizon Telescope (EHT), which is a combination of existing facilities into an interferometry array, the operation footprint is counted in the footprint of the individual facilities. The construction footprint covers the additional footprint due to the combination of the facilities.
(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 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, 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 ~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. 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 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 1283 ± 232 ktCO₂e, 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. While the annual 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 with space missions.

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 1054 ± 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 ± 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 ± 7.7 tCO₂e 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 ± 14.0 tCO₂e 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 für Astronomie in Heidelberg to be 18.1 tCO₂e yr⁻¹, dominated by 8.5 tCO₂e yr⁻¹ from flights, 5.2 tCO₂e yr⁻¹ from electricity use and 3.0 tCO₂e yr⁻¹ from heating. For the average Australian astronomer (including PhD students), ref. 6 estimated a footprint of ≥ 37 tCO₂e yr⁻¹, comprised of 22 tCO₂e yr⁻¹ for supercomputing, 6 tCO₂e yr⁻¹ from flights, 4 tCO₂e yr⁻¹ for powering the office buildings and 5 tCO₂e 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 GtCO₂ yr⁻¹ (corrected for emissions from land-use change), corresponding to a per-capita carbon sink of 2 tCO₂ 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 tCO₂ 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 ktCO₂ (mass-based) and 1,223 ktCO₂ (cost-based) and for the Square Kilometre Array we estimate the construction footprint to be 312 ktCO₂ and the annual operations footprint to be 18 ktCO₂ 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 rate of CO₂ emissions 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 year after 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 ktCO₂ yr⁻¹ compliant with 60 ktCO₂ 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

\[
\text{Carbon footprint} = \sum_i A_i \times EF_i
\]

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

\[
\text{Carbon footprint}_{c/m} = A_{c/m} \times EF_{c/m}
\]

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

\[
\text{Carbon footprint} = A_c \times EF_c + A_o \times T \times EF_o
\]

where \(A_c\) is the construction cost, \(A_o\) the annual operating cost, \(T\) the lifetime in years and \(EF_c\) and \(EF_o\) are the emission factors for construction and annual operations, respectively. For many activities, emission factors can, for example, be found in ref. 1. For databases does not exist, we developed enough 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 furtherem 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.

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 the data that were used to produce the papers. In a few case 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 not 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 initiative2). 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 estimates. For example, for the Sentinel-3B mission, an Earth observation satellite of the EU Copernicus programs, ref. 2 found that 25% 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. 2 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.

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 (LCMSA) framework developed by ref. 2 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 MIOs 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 NEACORE mission, a set of six nanosatellites for the exploration of asteroids by collision and flyby reconnaissance.

In the ref. 2 case study, the MIOs 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 MIOs mission. The payload has a wet mass of 286 kg and the assumed mission duration is 2 years. Reference 2 estimated the total carbon footprint of the mission to be 11,200 tCO₂e and a cost of €116 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 1.43 kg and the assumed mission duration is 6 months. Reference 2 estimated the total carbon footprint of the mission to be 8,780 tCO₂e and a cost of €41 million 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. 2 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 MIOs and NEACORE estimates differ by less than 5% 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 different 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. 2). 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.

Construction. Reference 2 has estimated the carbon footprint of the Giant Radio Array for Neutrino Detection (GRAND), an experiment that aims to detect ultra-high-energy cosmic rays with an array of radio antenna. The ref. 2 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

\[
\text{Carbon footprint}_{\text{construction}} = A_{\text{construction}} \times EF_{\text{construction}}
\]

where \(A_{\text{construction}}\) is the cost of 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 furtherem 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 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. 17, 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 and communications facilities (Table 2).

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 tCO₂e, 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) (personal communication). Using the E-ELT construction cost of 945 M€, quoted in the E-ELT construction proposal18 (converted to 2019 economic conditions), results in a monetary emission factor of 67 tCO₂e M€⁻¹, which is considerably smaller than the GRAND estimate and considerably lower than any sector-based estimate in ref. 17.

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 tCO₂e 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 tCO₂e M€⁻¹ and 2.3 tCO₂e M€⁻¹, respectively. Both footprints are dominated by energy use (71% for Paranal, 92% for La Silla), followed by commuting (11% for Paranal, 5% for 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. Arensault (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 tCO₂e M€⁻¹ for Paranal and 2.8 tCO₂e M€⁻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)19. Assuming 120 k€ per full-time equivalent (2019 economic conditions; ref. 20), 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, 19 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. 21 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 amount to 749 tCO₂e, dominated by power generation (63%) and transportation (31%). For an operations budget of 6.3 M€ for the same years22, this results in a monetary emission factor of 119 tCO₂e M€⁻¹ for CFHT operations, considered below the 20% uncertainty for Paranal. Due to the high emission factor of flights, the flight-related emissions may be underestimated in their study and alternative estimators for flight-related emissions23 indeed have yielded an estimate that is higher by a factor of two. Doubling the contribution of flights in the original calculation by ref. 21 would result in a total footprint of 923 tCO₂ 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. 21 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 emission factors 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.

**Adapted 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 1,800 tCO₂e M€⁻¹ for mineral products24. 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 Littoral mass of a €1 billion space mission launched with Ariane 5 ECA is about 790 tonnes25, while the E-ELT (which has a similar cost) has a mass of about 60,000 tonnes26. The space sector is in fact unique, and is characterized by low production rates, long development cycles and specialized materials and processes27.

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 included were constructed decades ago (ESO, personal communication). Using 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. 17, 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 the 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 queries with the same ADS query string used for the E-ELT and CFHT (ESO, personal communication). For the Paranal and La Silla, we obtained the number of unique authors who 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 peer-paper footprint of research infrastructures28. 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 codes 38. We therefore make our estimate by assuming that there exist at least 1,000 professional OIR telescopes 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 2021 39, yet not every astronomer is a member of the IAU. Reference 39 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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Author contributions
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 on the discussion section and reviewed the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
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Correspondence and requests for materials should be addressed to Jürgen Knödlseder.

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