NASA Astrophysics Division Technology Heritage Study

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Abstract

The National Aeronautics and Space Administration's (NASA) Astrophysics Division (APD) funds and manages missions and studies that seek to broaden our understanding of our place in the universe. These science missions are enabled by technologies developed through APD's technology development programs. APD has funded approximately seven different technology development programs over the last ten years which support basic research and target varying Technology Readiness Levels (TRLs). The funding has targeted technology for future space flight experiments as well as suborbital science investigations. To understand the overall impact of APD's investment on astrophysics technology advancement through their grants and contracts, APD engaged The Aerospace Corporation to conduct an independent, comprehensive Astrophysics Technology Heritage Study. The study was conducted in the 2021-2022 timeframe, first focusing priority on infusion of competed grants and general trends, followed by directed grants and further trend analysis and technology characterization. The study included three major components: a grants database, a missions database, and a survey of Principal Investigators (PIs). The study found that APD grants and contracts fund a healthy portfolio of technologies that resulted in an overall 62% infusion rate, as suborbital missions provide ample science and technology maturation and platform transition opportunities. Within the 62% of infused grants, 12% were infused into space missions and another 31% were suborbital. The study also looked at various other characteristics of the grant awards including the organizations they were awarded to and award trends by PI. Technology focus areas and detector types were also investigated, as well as technology platform transitions from on mission environment (e.g., suborbital to space). Additional feedback from PIs was also requested and evaluated including alternative benefits of grants and reasons development did, or did not, succeed.

Keywords:

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Optics

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1 Introduction

The National Aeronautics and Space Administration's (NASA) Astrophysics Division (APD) engaged The Aerospace Corporation ("Aerospace") to conduct an independent, comprehensive Astrophysics Technology Heritage Study. The purpose was to understand the overall impact of APD's investment on astrophysics technology advancement through their grants and contracts. The study was conducted in the 2021-2022 timeframe, first focusing priority on infusion of competed grants and general trends, followed by directed grants and further trend analysis and technology characterization. The study included three major components:

(1) Grants Database, a compilation & analysis of astrophysics technology grants from 2009-2020

(2) Missions Database, including space and suborbital missions from 2010-Future

(3) Principal Investigator (PI) Survey, a survey of over 300 2009-2020 grant recipients with question about the status of technology developments as well as non-technology benefits

The study found that APD grants and contracts fund a healthy portfolio of technologies that resulted in an overall 62% infusion rate, as suborbital missions provide ample science and technology maturation and platform transition opportunities. Within the 62% of infused grants, 12% were infused into space missions and another 31% were suborbital. Since the development lifecycle for astrophysics technologies is often longer than 10 years, this percentage would likely be even higher if the prior decade's grants were also considered. PIs cited lack of opportunity for space missions as the top reason for technologies not being infused, as Explorer mission opportunities are fewer than desired and Flagship opportunities occur approximately once a generation. Grants awarded have numerous benefits beyond their primary purpose, as they enable development of students/staff, lab/infrastructure, and more. A total of 120 unique organizations were found to have received grants, with most receiving only one. Nineteen organizations received 58% of all grants, with the top two (JPL and GSFC) receiving 19% of all grants.

2 Background

NASA APD has funded numerous grants program over the 2009-2020 period of study including competed programs such as Astrophysics Research and Analysis Program (APRA), Strategic Astrophysics Technology (SAT), Roman Technology Fellowships (RTF), NASA Earth and Space Science Fellowship (NESSF), Future Investigators in NASA Earth and Space Science and Technology (FINESST), and Segmented Mirror Technology Program (SMTP). APRA funds technologies in innovation/inception at Technology Readiness Level (TRL) 1-3 as well as experimentation TRL 3-9. SAT funds technology maturation TRL 3-6. RTF is solicited through both APRA and SAT and intended to provide opportunities for early career researchers to develop innovative technologies. The NESSF and FINNEST programs are graduate student designed programs with PI supervision. The final NESSF solicitation was in 2018 which was then replaced by the FINNEST program. SMTP were industry studies awarded to study next generation telescope technology needs.

Additionally, APD has provided funding for NASA directed and peer-reviewed and competed technology programs such as Internal Scientist Funding Model (ISFM). ISFM is intended to fund strategic science enabling technologies that leverage NASA unique facilities and capabilities. TRL levels used for this study were defined by NASA Procedural Requirement (NPR) 7123.1C Appendix E*.

3 Database Overviews

To support this study, three databases were created: 1) a database of all APD grants from selected programs during 2009-2020, 2) a database of all APD space and suborbital missions flown since 2010 or planned to be flown in the future, and 3) a database of survey responses from Principal Investigators (PIs) who received APD competed grants during 2009-2020. Analyses were conducted on each database individually and then cross referenced with each other to assess the overall picture of APD technology development.

3.1 Grants Database

The grants database includes details of grants provided by APD for competed grant programs previously described: APRA, SAT, RTF, NESSF, FINESST, SMTP.† Only grants solicited during 2009-2020 were included. This solicitation year is referred to as Research Opportunities in Space and Earth Sciences (ROSES) year.‡ Grants for each program were not solicited every year; **Table 1** displays the grant programs that were solicited in each ROSES year.

Table 1 Grant programs solicted in each ROSES year. "N/A" indiciates the program was not solicited that year. Multiple checkmarks indicate multiple solicitations in that year.

Program	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
APRA	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	N/A	✓
Directed	N/A	✓	N/A	✓	N/A	N/A	N/A	✓	N/A	✓	N/A	N/A
Explorer	N/A	✓	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
ISFM	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	✓	✓	N/A	N/A
NESSF/FINESST	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓✓	N/A
RTF	N/A	N/A	✓	✓	N/A	✓	✓	N/A	N/A	✓	✓	✓
SAT	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	N/A	N/A
SMTP	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	✓	N/A	✓	N/A

* https://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_7123_001C_&page_name=AppendixE

† RTF awardees are selected from that years' pool of APRA awardees; this study assesses APRA and RTF as separate programs. FINESST is a follow-on program to NESSF with similar, but not identical, criteria; this study assesses NESSF and FINESST as a single program. SMTP is also known as System-Level Segmented Telescope Design (SLSTD).

‡ ROSES is NASA's Science Mission Directorate (SMD) omnibus grant solicitation program. ROSES years correspond to the year that proposals are solicited; grants are typically selected the following calendar year after solicitation and funded within the next several years after selection.

In total, the grant database contains 850 grants of which the majority, 536 or 63%, were from APRA. Fig. 1 displays the breakdown of grants by program.

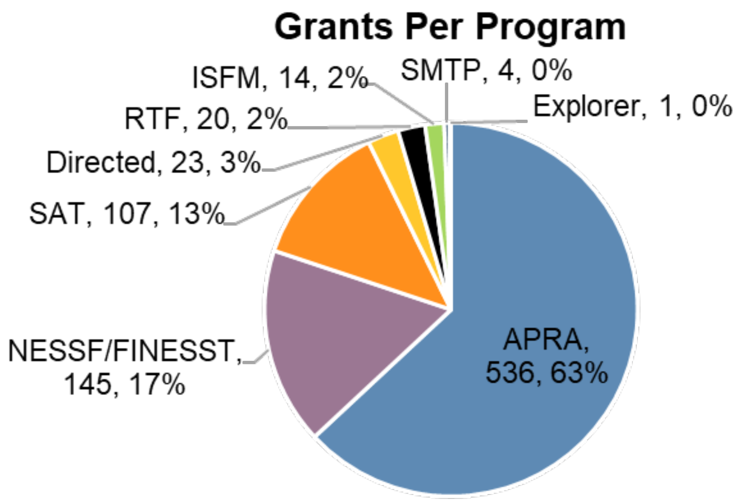


Fig. 1 Breakdown of grants per program

The 850 grants in the database were received by 421 unique PIs across 121 unique organizations. To help frame the impact of the grants, a deeper investigation into grant PIs and their organizations was conducted.

3.1.1 PI analysis

Fig. 2 displays a breakdown of PIs by the number of grants each received from 2009-2020. PIs were most likely to receive few grants each, with most PIs (55%) receiving only a single grant and the trend sharply decreasing as the number of grants per PI rose. A small subset of PIs greatly outpaced other PIs: 17 PIs (4%) received six or more grants each, including one PI that received 10 grants during 11-year period.

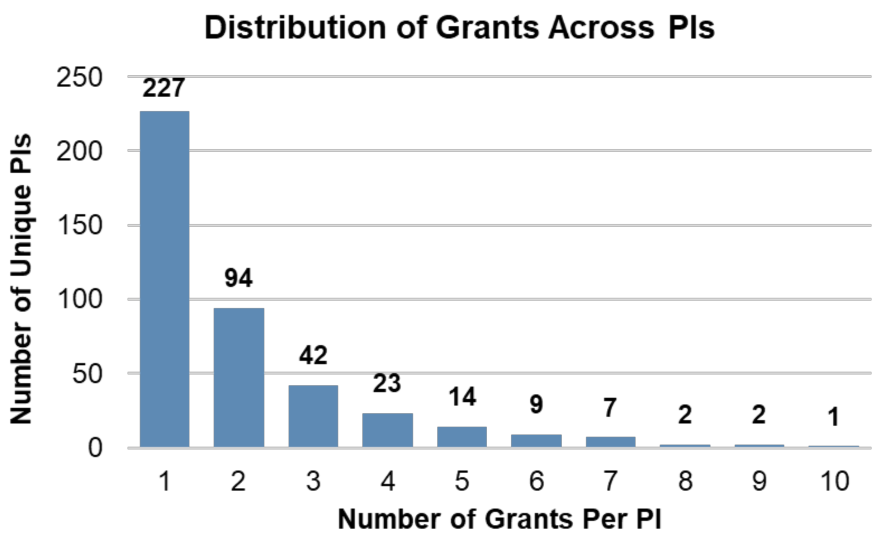


Fig. 2 Distribution of APD grants across PIs

With most PIs receiving only one grant during 2009-2020, it is not surprising that the growth in first-time PIs per year is roughly linear. As shown in Fig. 3, an average of 32 PIs received an APD grant for the first time each year from 2010-2020. This is not a perfect assessment; because the grants database did not include grants prior to 2009, PIs who received grants prior to 2009 could not be identified. This may account for the above-average number of first-time PIs in 2010 and 2011. 2020 saw a drop in first-time PIs.

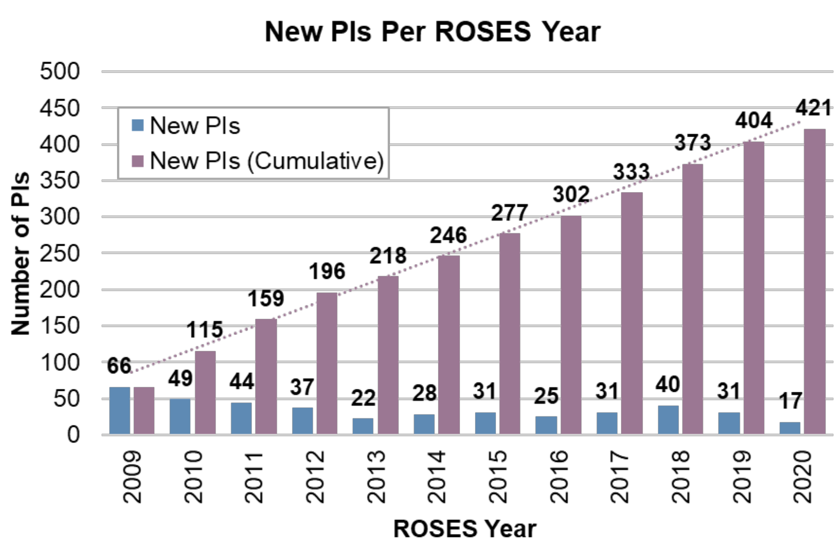


Fig. 3 First-time PIs since 2009 per ROSES year

3.1.2 Organization analysis

Of the 121 unique organizations in the grants database, most (74%) were educational with the remaining 26% split between NASA Centers, non-NASA government agencies (including one non-US agency), commercial organizations, and non-profit organizations. NASA Centers significantly outpaced other types of organizations in the number of grants received by each organization. Only four NASA Centers received APD grants; however, as shown in Fig. 4, these four Centers received 211 grants, or 25% of all grants in the database.

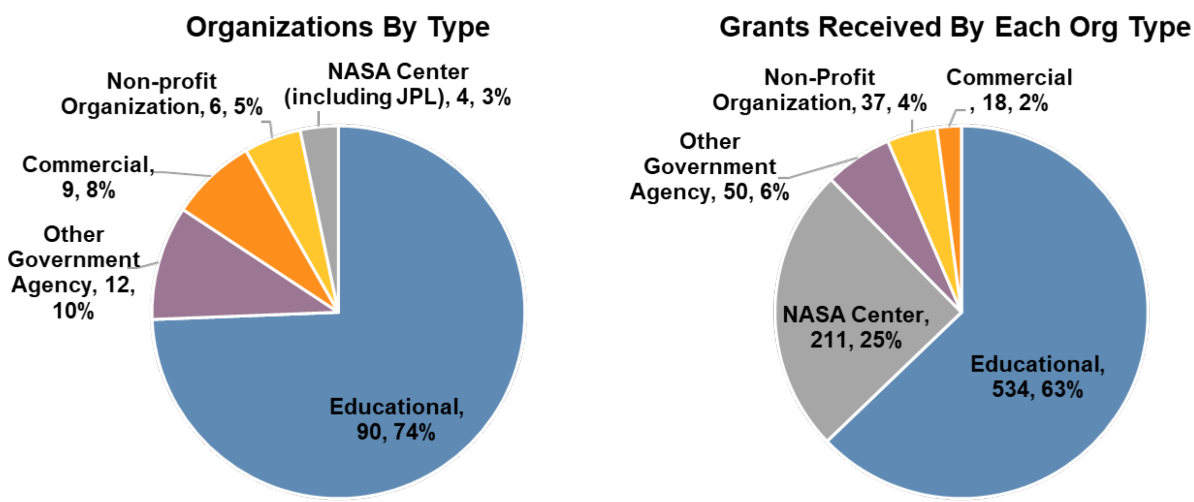


Fig. 4 Breakdown of organizations by type, showing number of organizations (left) and number of grants received by each type (right)

This trend of a small number of organizations significantly outpacing others is also seen in the distribution of grants across organizations (Fig. 5). Whereas 73% of organizations received seven grants or less each, a subset of 20 organizations (17%) received ten or more grants each. These 20 organizations received over half (61%) of all grants in the database.

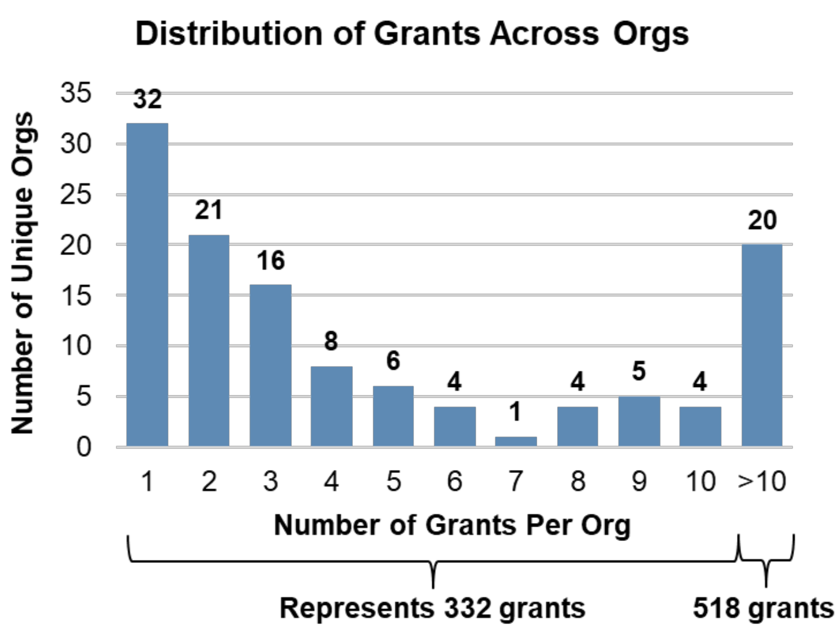


Fig. 5 Distribution of grants across organizations

The organizations that received the most grants each were NASA Centers, specifically, NASA Goddard Space Flight Center (GSFC) and NASA Jet Propulsion Laboratory (JPL) (Fig. 6). The University of Colorado Boulder had the third most grants and the most of any educational organization. Most of the other top organizations by number of grants received were also educational.

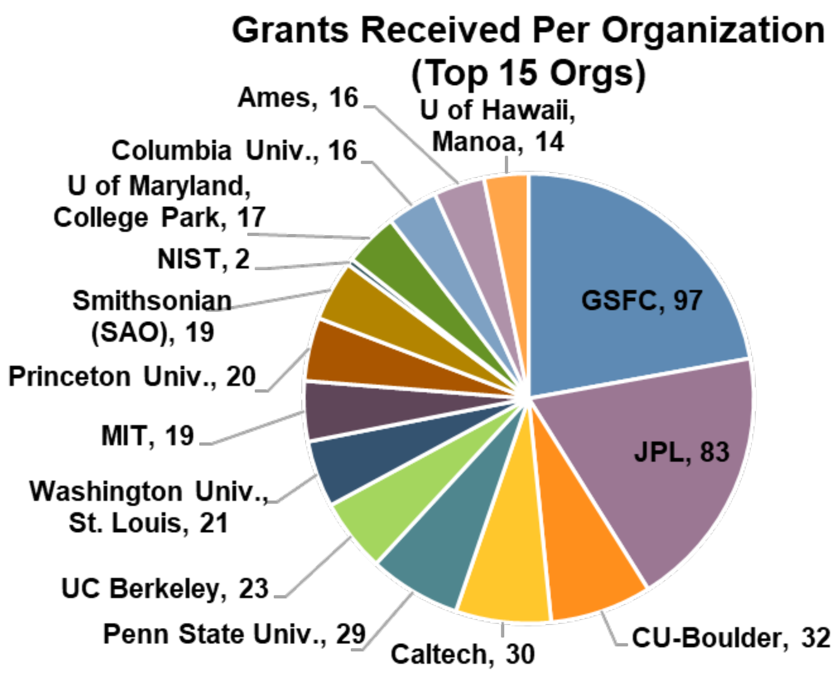


Fig. 6 Top 15 organizations by number of grants received each

3.1.3 Grant-developed technologies categorization

Each grant in the database was categorized by the technology type that the grant developed. Categorization was taken from the Astrophysics Technology Development Portfolio[1] and modified to identify grants which contributed to flight missions. For this study, grants that supported flight missions were considered technology development, or more specifically, technology demonstrations.

As shown in Fig. 7, most grants in the database (75%) were for technology development and flight missions. Of the grants that developed technologies, most grants supported detector development, followed by optics, and coronagraph development.

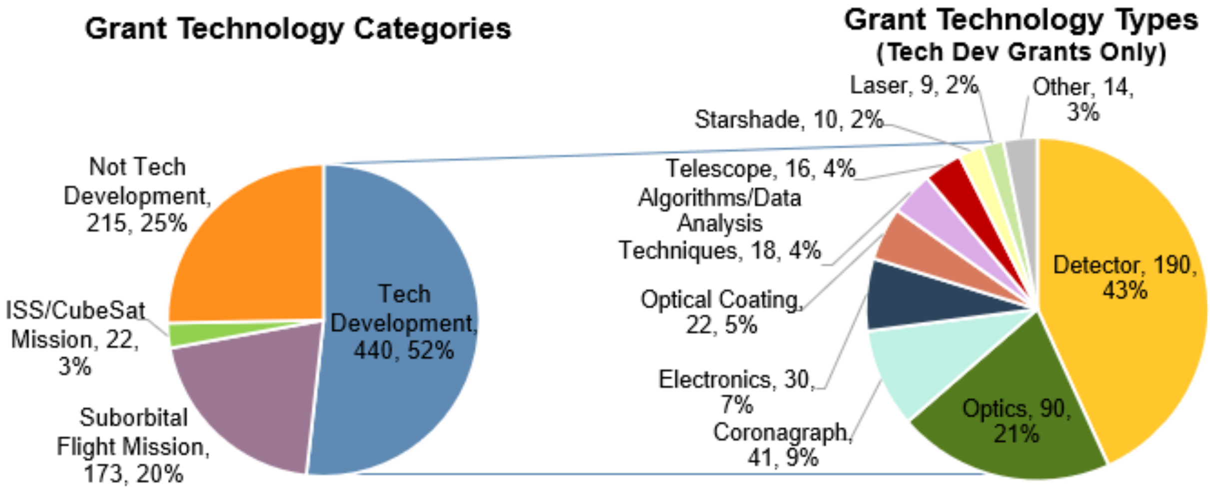


Fig. 7 Technology categories (left) and types (right) developed by APD grants

3.1.4 Detector development grant categorization

Among the 190 grants devoted to the detector technology type, 149 were focused purely on detector development, while 41 of them focused on detector supporting technologies and other related items. The 149 detector development grants were further characterized by signal type and detector type. Signal types were taken from the Astrophysics Technology Development Portfolio and further normalized as necessary. Detector types were normalized from reviewing the individual grant descriptions.

As shown in Fig. 8, most detector development grants were focused on x-rays (31%), followed by infrared (25%), ultraviolet (13%), and submillimeter (12%). Also, the most common detector technology development involved transition edge sensors (TES) at 19%, kinetic inductance detectors (KID) at 17%, complementary metal-oxide semiconductor (CMOS) at 7%, and micro-channel plates (MCP) at 7%.

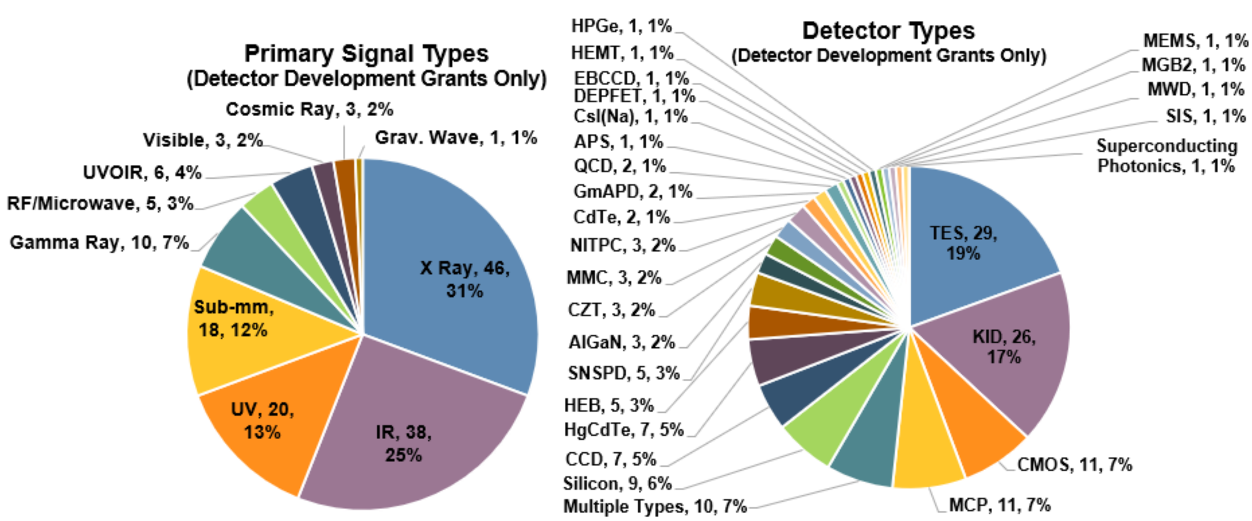
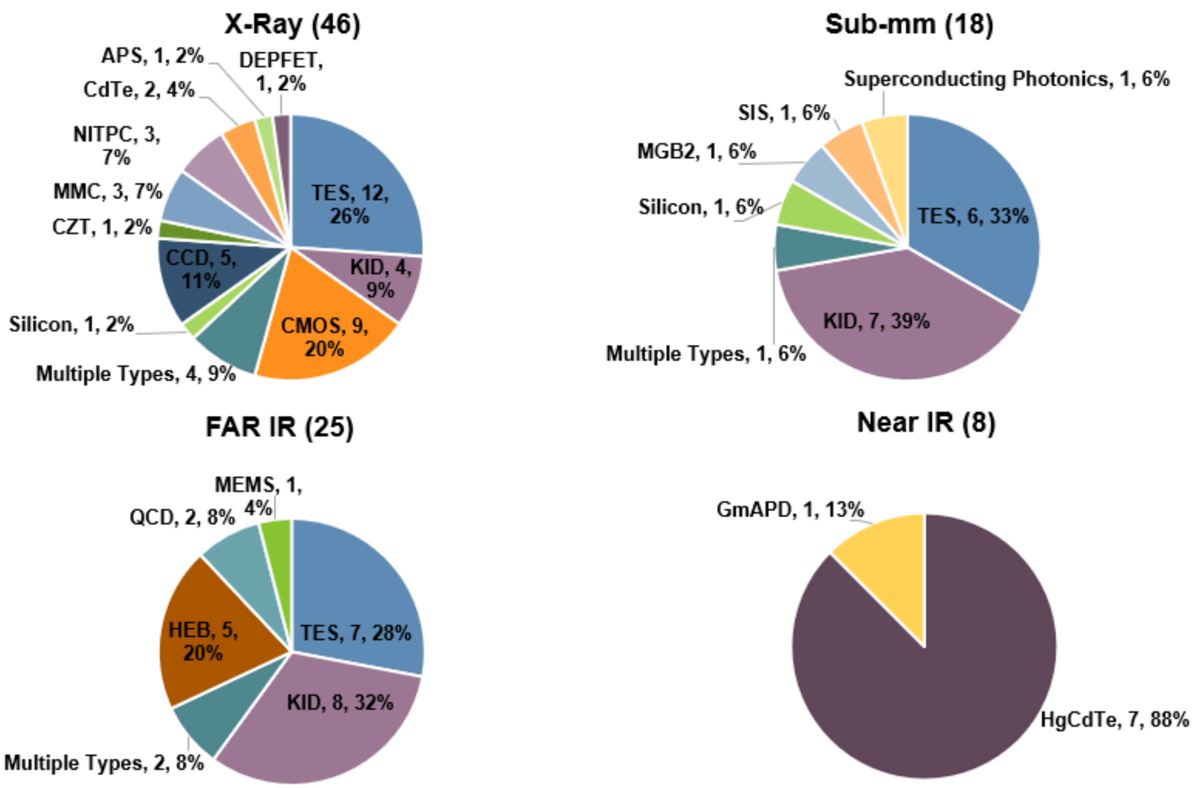


Fig. 8 Detector development grant signal types (left) and detector types (right)

Signal types and detector types were further examined to search for commonalties between the two categories. Fig. 9 shows pie charts following top to bottom and left to right for the most common signal types including x-ray, submillimeter, far-infrared, near-infrared, ultraviolet, gamma-ray, ultraviolet-optical-infrared (UVOIR), and radio-frequency/microwave. The x-ray signal type had the most different detector technologies researched for it in addition to having the most grants of all signal types. Conversely, the near-infrared, UVOIR, and radio frequency/ microwave signal types only had a few signal types researched for them. Among the superconducting detectors, TES and KIDS were found to be most popular by the proposing community. Furthermore, TES being one of the most commonly researched detector technologies, was found in several signal types including: x-ray, submillimeter, far-infrared, and radio-frequency/microwave. KID detectors similarly were found in x-ray, submillimeter, far-infrared, UVOIR, and radio-frequency/microwave applications.



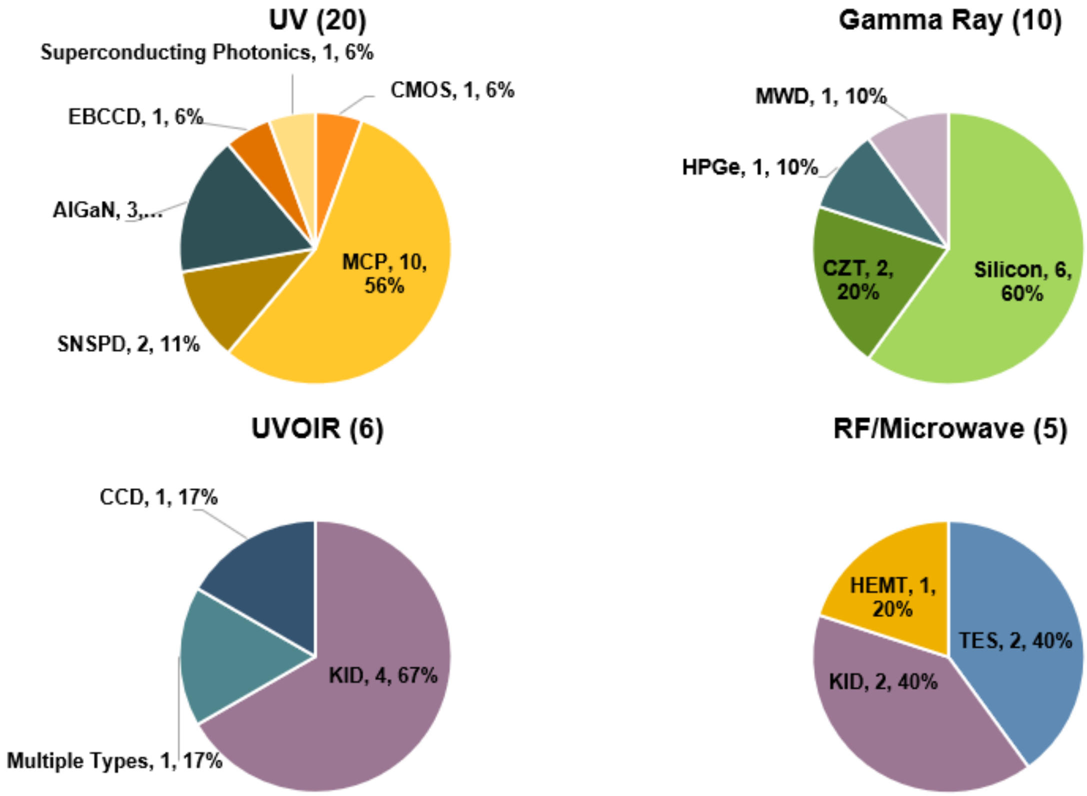


Fig. 9 Detector type technologies developed by signal type

3.2 Missions Database

The missions database includes details of all APD space, suborbital, and ISS missions that were flown on or after January 1, 2010 or were planned to fly in the future. In addition, two 2009 space missions, Kepler and WISE, and 11 ESA- or JAXA-led missions that carried US-developed instruments were included. For suborbital missions that flew multiple times, only the first flight (2010 or later) was included. Missions were identified through a combination of public sources and PI survey responses. In total, the missions database contains 125 missions and 228 instruments.

3.2.1 Mission type and status analysis

Of the 125 missions, 62 had already flown, 27 were selected but not flown, 27 were still in the proposal or pre-formulation stages, and 9 were cancelled or discontinued. Fig. 10 shows all APD missions broken down by launch year and status.

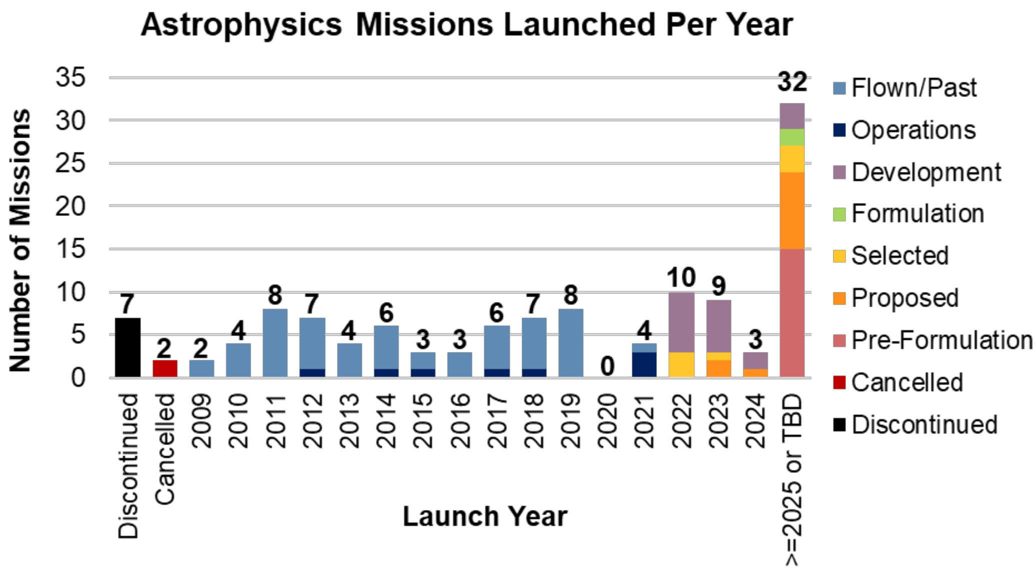


Fig. 10 APD missions by launch year and status

As shown in Fig. 11, over half of the 125 missions (69 or 26%) were suborbital, with the most common mission types being balloons (43 or 34%) followed by spacecraft (34 or 27%) and sounding rockets (25 or 20%).

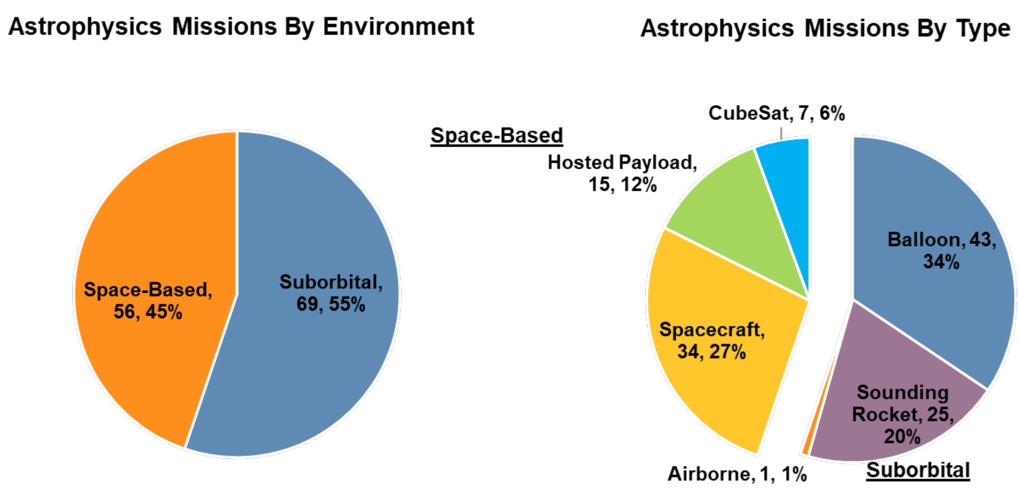


Fig. 11 APD missions by environment (left) and mission type (right)

3.2.2 Instruments analysis

Instruments flown on each mission in the database were identified using public sources. As shown in

Table **2**, Balloon and CubeSat missions tended to fly fewer instruments each, whereas sounding rocket, spacecraft, and hosted payload missions tended to fly more instruments each. The database also included one airborne mission which flew 12 instruments total, but not simultaneously.

Table 2 Average and maximum number of instruments per mission.

Mission Type	Average Instruments Per Mission	Maximum Instruments Per Mission
	Suborbital	
Balloon	1.2	4
Sounding Rocket	1.9	6
Airborne	12	12
	Space-Based	
Spacecraft	1.9	4
Hosted Payload	2	6
CubeSat	1.3	3

3.3 Survey

To identify and understand the eventual outcome and benefits of each APD grant, a survey was sent to 331 APD grant PIs. The survey was developed using the commercial software product, LimeSurvey, and included logic that customized the survey based on each PI's grants and responses. The 331 PIs surveyed were selected after a preliminary review identified them as having likely received at least one technology development grant between 2009-2020. This included grants for software development, modeling in support of hardware development, and mission flights or re-flights. PIs of APRA grants for laboratory astrophysics or ground-based observation grants also received the survey.

The survey included a mix of yes/no question, short text responses, and open-ended comments. PIs were asked if their technology development efforts had been infused and if they were still developing the technologies today. If relevant, PIs were asked to provide their opinion on why their technologies were not infused or had stopped developing. PIs were also asked for details of their flight missions (if their technologies were infused), the technology readiness level (TRL) of their technologies, other funding sources they used, transitioned technology development efforts, and alternative benefits of their grant efforts beyond infusion. Definitions and examples were provided for most questions included questions about infusion, TRL, and alternative benefits. PIs who received multiple grants were asked to answer each question for each grant; however, the survey questions were formatted so that PIs could respond for multiple grants simultaneously. The survey remained open for 2 months during which time 225 full and partial responses (68%) were received (Fig. 12). PIs were more likely to respond to the survey if they had received several grants.

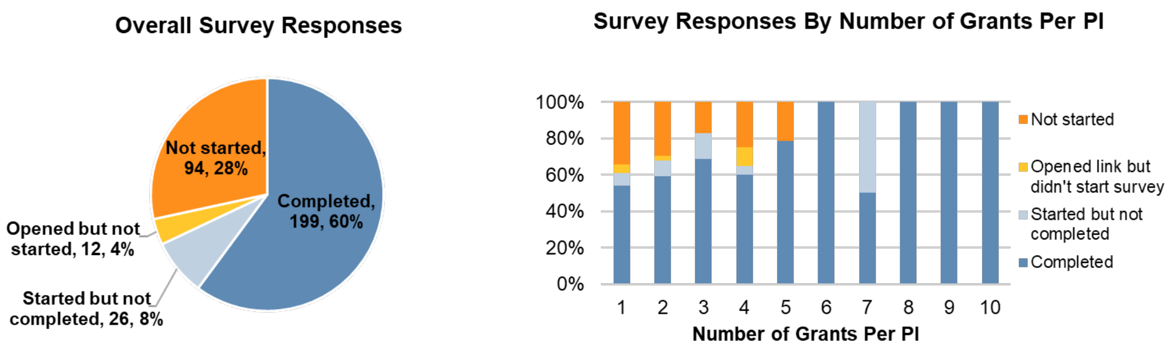


Fig. 12 Survey response metrics: overall responses (left), responses by grants per PI (right)

4 Analyses

The 225 PIs that responded to the survey provided details for 521 grants. Of these 521 grants, 458 (88%) were assessed to identify the result of each grant effort. The remaining 12% of grants were determined to be for non-technology development efforts and were excluded from technology development analyses, but still included in other analyses such as alternative benefits. Fig. 13 shows a breakdown of all grants in the grants database by inclusion in the survey and in the analyses. Overall, 57% of APD technology grants selected from 2009-2020 received a survey response and were analyzed.

A broad definition of technology development was utilized for this study. Efforts were considered technology development if they involved hardware development at any TRL, including conceptual design to integration and operation, software development, modeling, simulation, or process or algorithm development to support hardware development, or technology demonstrations and mission flights, including re-flights of heritage hardware. Data analysis, theoretical research, laboratory astrophysics efforts, and ground-based observations were not considered as explicit technology development.

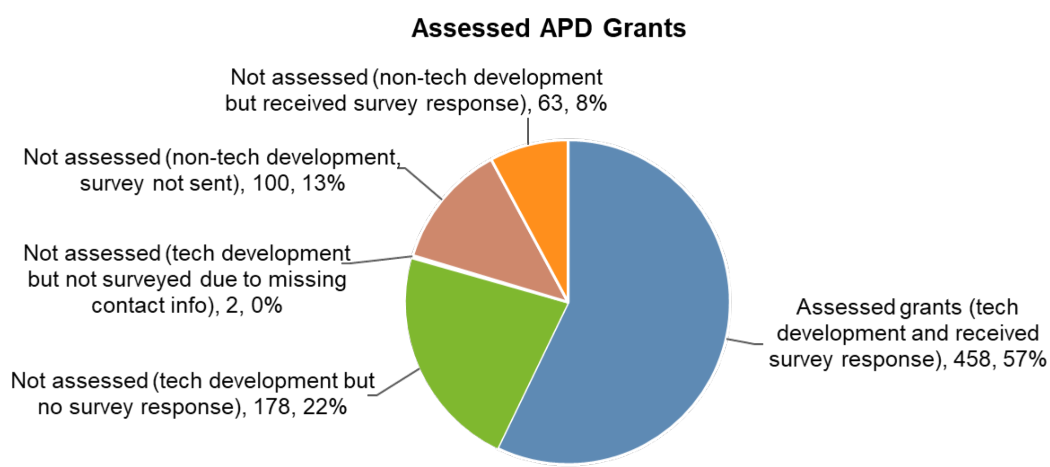


Fig. 13 2009-2020 APD grants by survey responses and inclusion in analyses

4.1 Survey Response Normalization

Prior to analyzing survey responses, responses were reviewed and normalized by modifying answers to yes/no questions to be consistent with comments. In some cases, data for grants were normalized because PIs identified the grant as not being infused but later commented that the developed technology had been flown. In other cases, PIs indicated that they had stopped developing their technology but later commented that the effort was continuing with the support of a later grant. In total, the current-day status of 43 grants was normalized.

Survey responses regarding additional funding sources and related or transitioned development efforts were also normalized for consistency and to consolidate PIs' responses. For example, many PIs stated that their technology development efforts were continuing with the support of later grants; however, they did not include the later grant when listing additional funding sources used. These questions were normalized for over 100 grants.

4.2 Grant Infusion Analysis

In this study, infusion was defined as the selection of a technology to fly on a suborbital or space-based mission. As shown in Fig. 14, a majority (62%) of APD grants selected during 2009-2020 resulted in technology infusions. However, mission infusions are found to have occurred at varying stages in the mission lifecycle and this calculation includes proposed technologies and technologies selected for discontinued missions. Within the infusion total, 43% of grants were infused into confirmed missions, here meaning missions in the selected or later stages, which includes 31% suborbital missions and 12% space missions. Another 16% were infused into unconfirmed missions (in pre-formulation or proposed), and 3% were infused into discontinued or unspecified missions. Another 30% of technologies were not mature enough for infusion at the time of the survey. Only 6% of grants resulted in a mature technology that was never infused. 2% of grants had an unknown status because only partial survey responses were received for them.

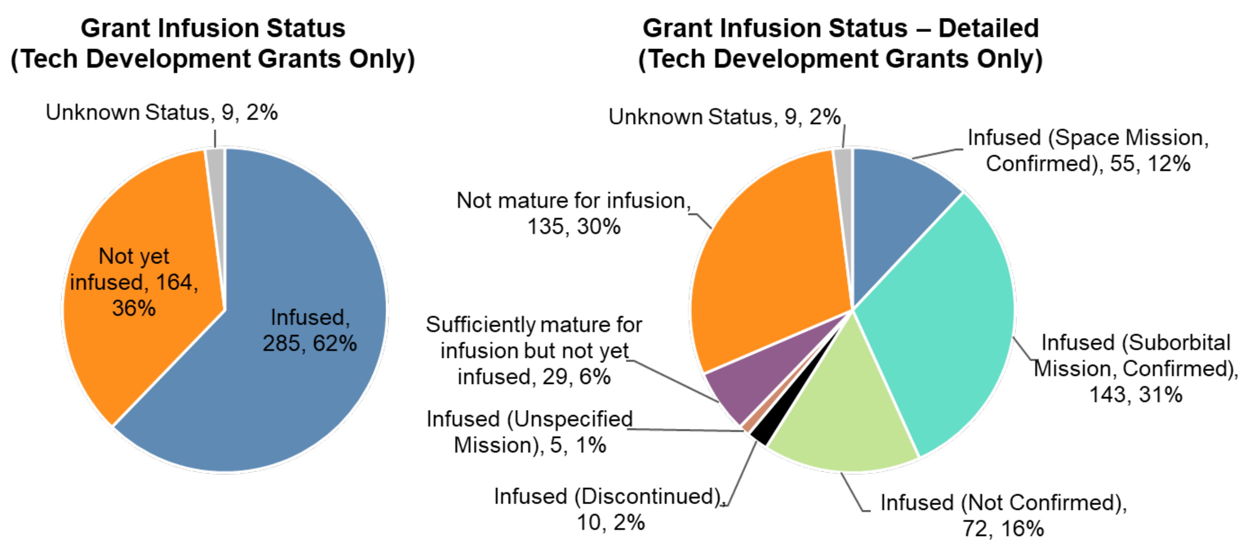


Fig. 14 Infusion status of technology development grants

The 285 infused grants contributed to technologies flown on both space-based and suborbital missions (Fig. 16). Just over half (52%) of infused grants contributed to suborbital missions. Most grants contributed to technologies flown on balloons followed by spacecraft missions.

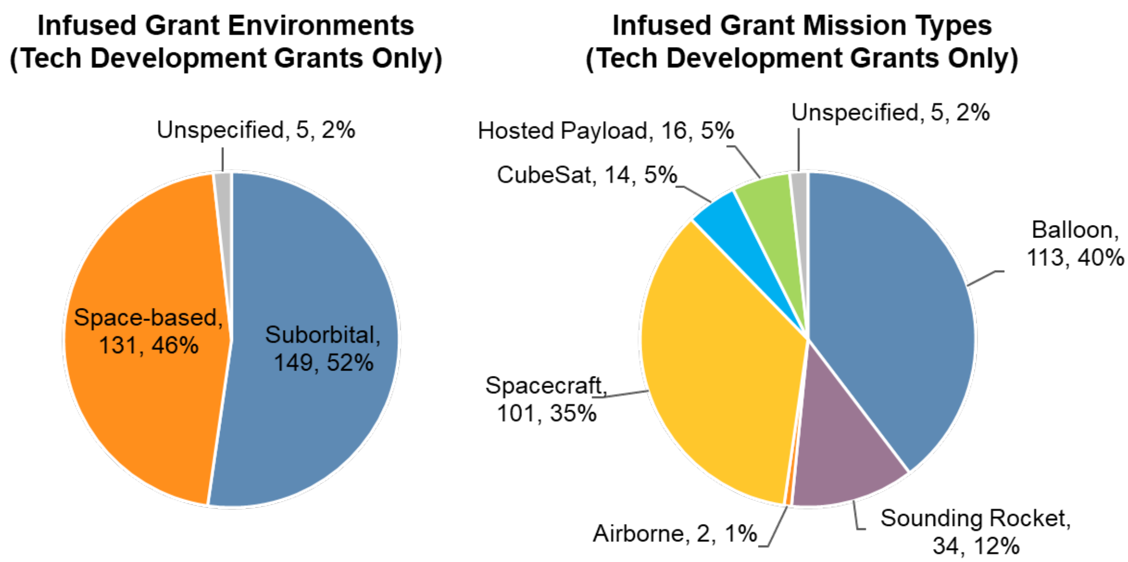


Fig. 15 Mission environments and types that infused grants contributed to

Fig. 16 shows a breakdown of infused grants by both mission type and mission status. Most grants contributed to flown balloon missions, followed by pre-formulation spacecraft missions and developing balloon missions.

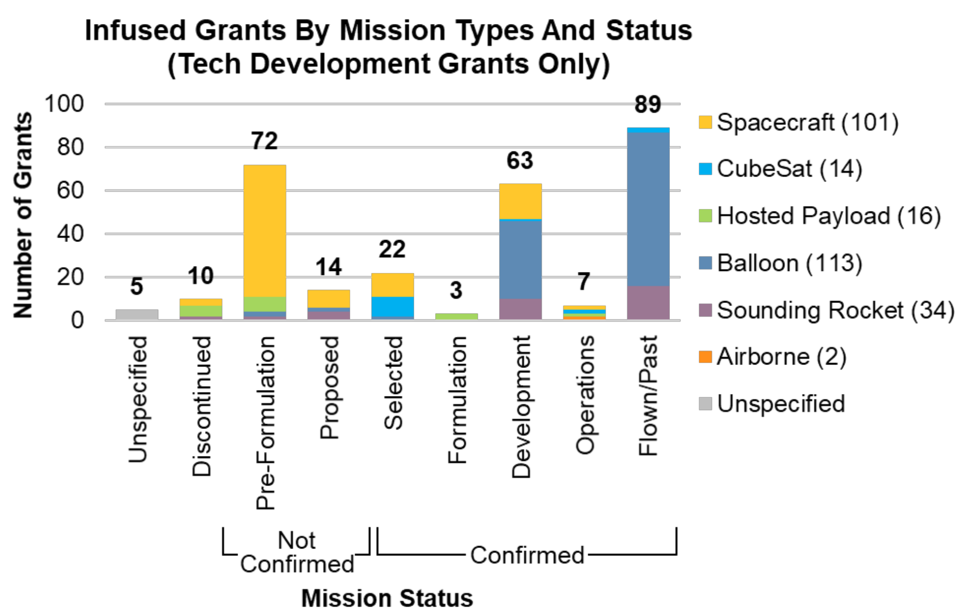


Fig. 16 Mission types and statuses that infused grants contributed to

Nearly all (94%) infused APD grants contributed to APD sponsored missions (Fig. 18). Only 2% of infused grants contributed to non-APD missions, while 4% of infused grants were undetermined. Non-APD missions contributed to included three spacecraft missions from other

NASA divisions (OSIRIS-REx, GOLD/ICON, and Europa Clipper), MAMBO, a U.S Department of Energy CubeSat mission, and LIFE, a European Space Agency balloon mission.

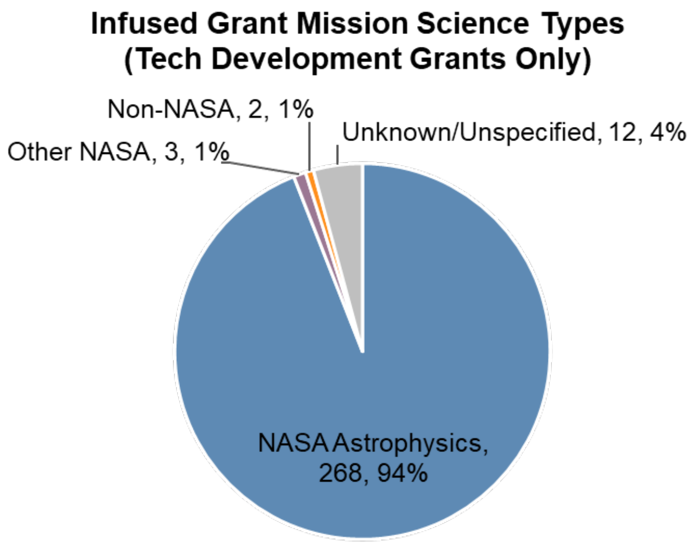


Fig. 17 APD grants versus APD sponsored missions

4.2.1 APD missions and infused APD grants cross-database analysis

Of the 125 APD missions in the missions database, 61% were confirmed to be funded by APD grants selected from 2009-2020 (Fig. 18). As this study did not assess grants selected prior to 2009, the actual total percentage of APD missions that received APD grant funding is likely to be greater than 61%. This is because many technologies flown after 2010 were likely in development (and received grants) prior to 2009.

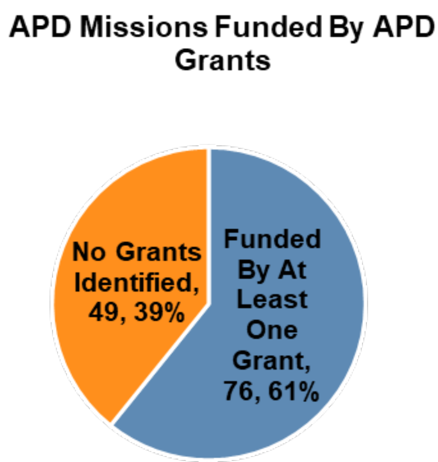


Fig. 18 APD grants funding status of APD missions (assessing grants selected 2009-2020 and missions flown 2010-future)

A deeper look at missions funded by (and not funded by) APD grants found that suborbital missions were more likely than space-based missions to be funded by grants (Fig. 19). Additionally, a greater percentage of missions not confirmed to be infused were funded compared to missions confirmed to be infused. This may be because missions flown in the 2010-2020 decade may have been funded by grants prior to 2009 which were not included in this study.

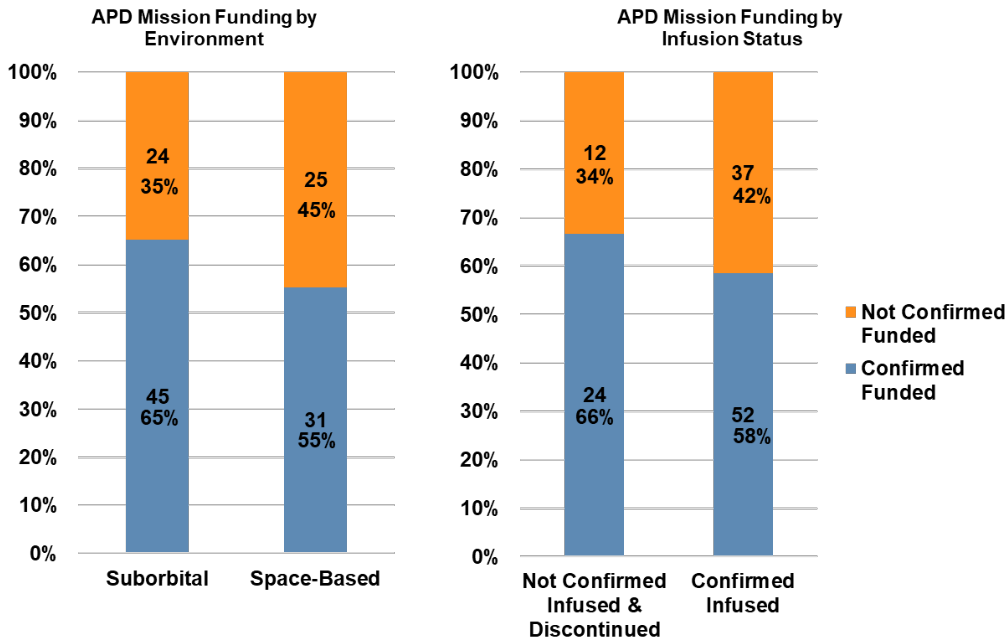


Fig. 19 Infusion status and environment of APD missions by APD grant funding status

4.2.2 Why technologies were not infused

To identify the factors preventing technologies from being infused, PIs were asked to provide their opinions on why their technologies were not infused. Only PIs who indicated that their technologies were ready for infusion, but not infused, were asked to provide a comment. This resulted in comments for 57 grants from 41 PIs. Comments were reviewed to identify common themes which were then used to develop common cause categories for technologies not being infused. Each grant was binned into at least one category and could be binned into any number of categories.

As shown in Fig. 20, the most common reason mentioned by PIs for not infusing their technologies was NASA Decision Making/Policy which affected 16 grants. The specific reason mentioned by PIs was a lack of mission opportunities. Other reasons that PIs mentioned were a community preference for competing technologies, technology roadblocks including both development issues and industry market factors, not enough time having passed since development ended, and proposals not being submitted yet.

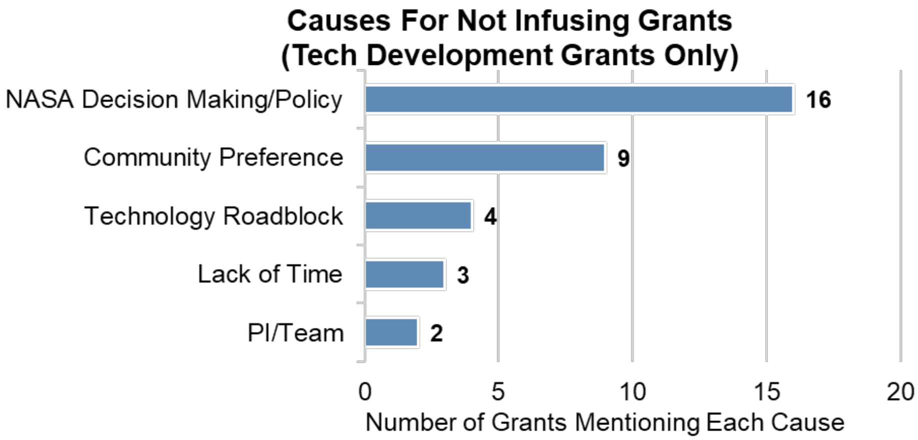


Fig. 20 PI opinions regarding why technologies were not infused; grants can be counted multiple times

4.3 Technology Heritage & Platform Transitions Analysis

Developing technologies may be applied in a variety of applications as both proof-of-concept and science opportunities. Many technologies also leverage prior developments. To showcase these aspects of the technology development pipeline, data from this study was used to trace the heritage of technologies from one flight mission to the next. Emphasis was given to technologies that transitioned platforms, being technologies that were proven in the suborbital environment and were then further developed for the space environment, or vice versa.

Some examples of platform transitions are shown below in graphical form. Fig. 21 shows a heritage trace of a Compton telescope technology. Fig. 22 shows a heritage trace of an international collaboration studying high energy cosmic rays. Fig. 23 shows a heritage trace a balloon mission with numerous flights that transition into an International Space Station (ISS) mission.

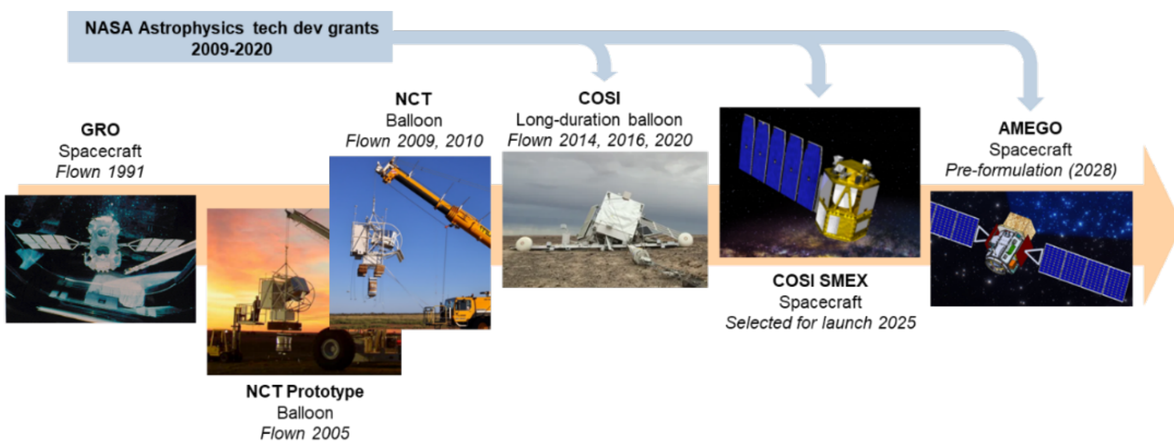


Fig. 21 Compton telescope heritage trace with platform transition

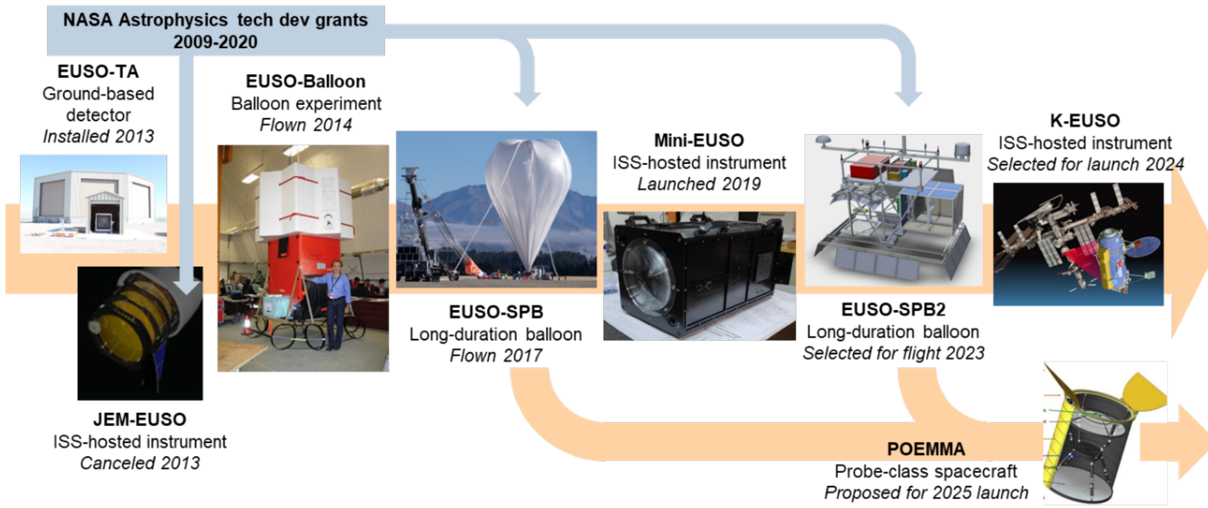


Fig. 22 International collaboration studying cosmic rays heritage trace with platform transition

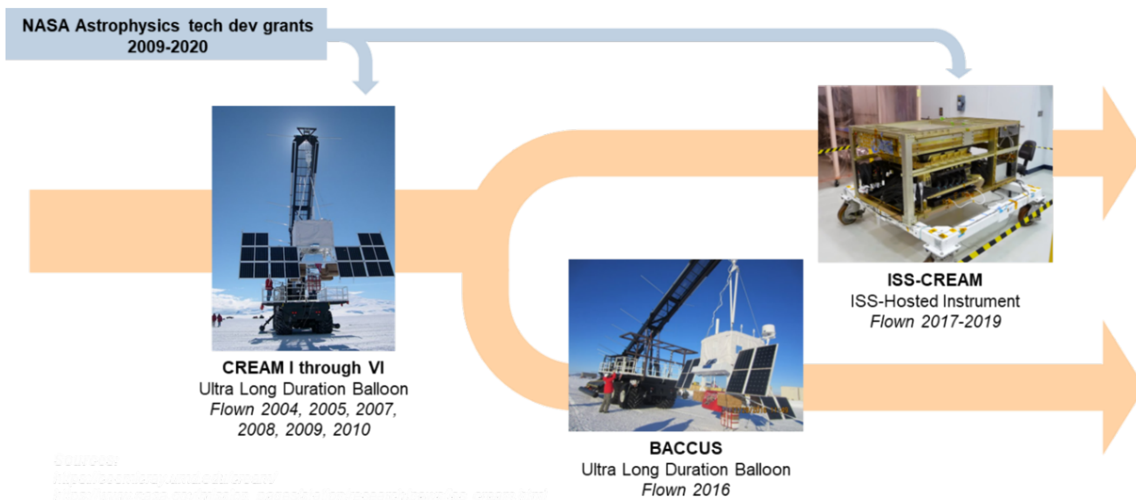


Fig. 23 Compton telescope heritage trace with platform transition

Infused grants were also comprehensively reviewed to identify missions that transitioned platforms. Fig. 24 shows a summary of this analysis. Of the 334 grants that were found to have supported an infused mission, 126 (38%) were also found to have contributed to a platform transition. Of the 125 missions in the database, 44 (35%) where found to have been a part of a platform transition. Additionally, Table 3 shows a summary of missions found in each identified platform transition.

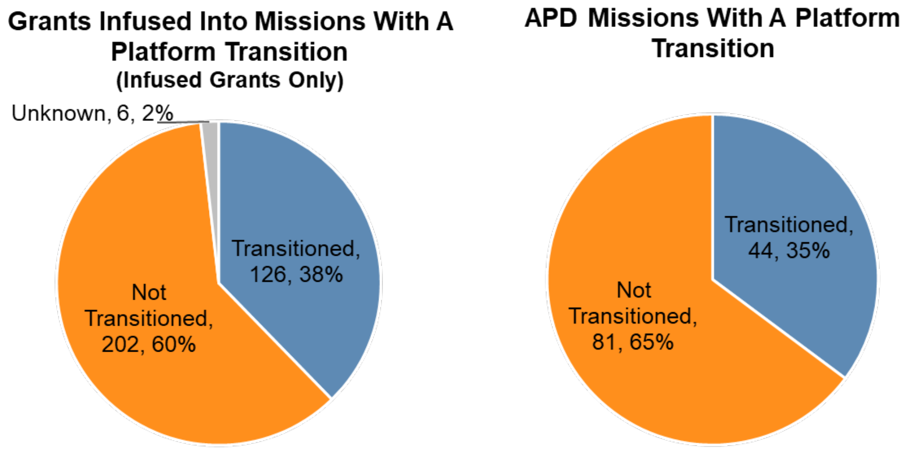


Fig. 24 Grants (left) and missions (right) that transitioned platforms

Table 3 Platform transitions supported by APD grants.

Earlier Mission(s)	Later Mission(s)	Transitioned Technology
	Suborbital → Space-Based Platform Transitions	
• JEM-EUSO (ISS-hosted instrument/cancelled) • EUSO-SPB (balloon)	• Mini-EUSO (ISS-hosted instrument) • POEMMA (spacecraft)	• Instrument (EUSO)
• TIGER (balloon) • SuperTIGER (balloon) • HELIX (balloon)	• HNX CosmicTIGER (spacecraft/not selected) • TIGERISS (ISS-hosted instrument)	• Instrument (TIGER) • SiPM-based scintillator detectors (HELIX)
• ProtoEXIST (balloon)	• EXIST (spacecraft/not selected) • HSP (spacecraft) • 4piXIO (spacecraft)	• Instrument (HET/HREXI)
• CREAM (balloon) • BACCUS (balloon)	• ISS-CREAM (ISS-hosted instrument)	• Instrument (CREAM)
• OGRE (sounding rocket)	• Lynx (spacecraft)	• Grating spectrometers
• GRAPE (balloon)	• LEAP (ISS-hosted instrument)	• Unknown
• EBEX (balloon)	• PICO (spacecraft)	• Transition edge sensors • Readout technology

• CIBER (balloon) • CIBER-2 (balloon)	• SPHEREx (spacecraft)	• Unknown
• Unknown sounding rocket missions • Unknown ISS-hosted instrument	• Europa Clipper UVS (spacecraft)	• Unknown
• DEUCE (sounding rocket) • SISTINE (sounding rocket)	• ESCAPE (spacecraft)	• Borosilicate-glass MCPs • Detector XDL readout
• WRX-R (sounding rocket)	• BlackCAT (CubeSat)	• Off-plane reflection grating array • H2RG hybrid CMOS detector • Camera interface board
• SHIELDS (sounding rocket)	• HabEx (spacecraft) • LUVOIR (spacecraft)	• FUVUV/Visible Photon Counting and Ultralow Noise Detectors
• FOXSI (sounding rocket)	• FOXSI (spacecraft)	• Instruments (details unknown)
	Space-Based → Suborbital Platform Transitions	
• BLAST (balloon) • Herschel/SPIRE (spacecraft)	• BLAST-POL (balloon) • BLAST-TNG (balloon) • TIM (balloon)	• Detector arrays (Herschel) • Instrument (BLAST/TIM)
• JWST (spacecraft) • FORTIS (balloon)	• NG-FORTIS (balloon) • OA-FORTIS (balloon)	• Next Generation Microshutter Arrays (NGMSA)
• Herschel HIFI (spacecraft)	• ASTHROS (balloon)	• Heterodyne instrument/receiver technology
	Ground → Space-Based Platform Transitions	
• LIGO (ground) • GRACE-FO/LRI (spacecraft)	• LISA Pathfinder (ESA spacecraft) • LISA (ESA spacecraft)	• Instrument concept (from LIGO) • Photo receivers, phase measurement systems, laser control systems (from GRACE-FO/LRI)
• EDGES (ground)	• DARE (spacecraft)	• EDGES is a ground-based pathfinder for DARE
• SCExAO (ground)	• EXCEDE (spacecraft)	• SCExAO is a functioning testbed prototype for EXCEDE

Multiple Platform Transitions		
• GRO/COMPTEL (spacecraft) • NCT (balloon) • COSI (balloon)	• COSI SMEX (spacecraft) • AMEGO (spacecraft)	• Instrument (Compton telescope)
Space-Based → Airborne Platform Transitions		
• Herschel/HIFI (spacecraft)	• SOFIA/GREAT (airborne)	• Instrument (HIFI/GREAT)

4.4 Grant Development Analysis

As shown in Fig. 25, most APD technology development grants contributed to technologies that are still being developed today. Only 16% of grants supported technologies that are no longer in development.

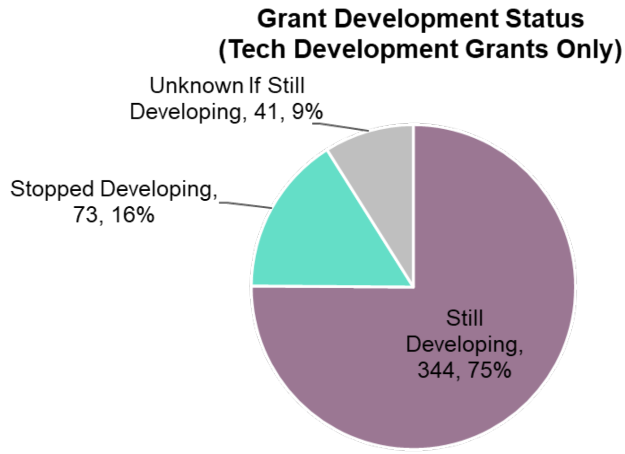


Fig. 25 Development status of technology development grants

As shown in Fig. 26, infusion status does not have a strong correlation with development status. Many technologies that grants contributed to were both infused and still being developed. This is reasonable when considering the large percentage of suborbital infusions, as suborbital missions can be used to develop flight heritage for instruments that are eventually intended to fly in the space environment.

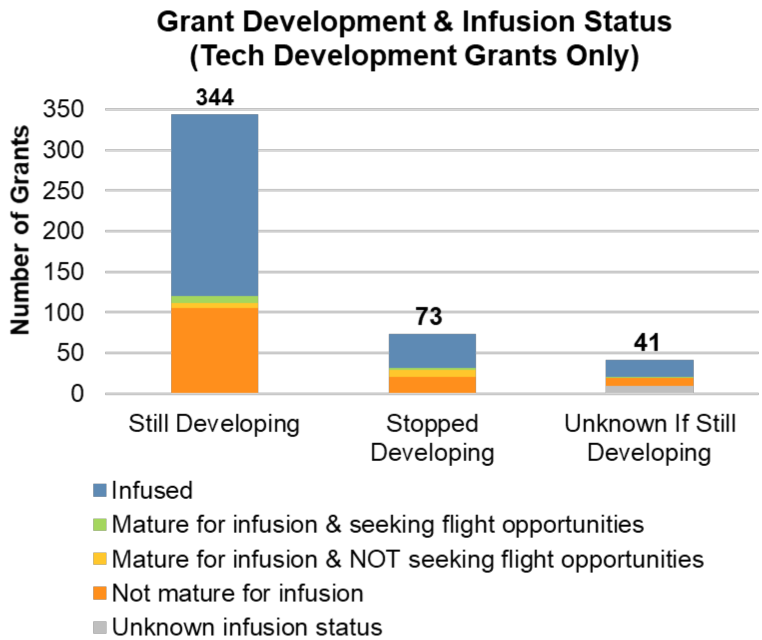


Fig. 26 Infusion and development statuses of technology development grants

Of the 73 grants (16%) that contributed to technologies which are no longer being developed, 41 grants contributed to infused technologies, 20 contributed to immature technologies, and only 12 contributed to technologies that were matured but never infused.

4.4.1 Why technologies stopped developing

To identify the factors causing development of technologies to stop, PIs were asked to provide their opinions on why their technologies stopped developing. Only PIs who stated that they are no longer developing their technologies were asked to provide a comment. This resulted in comments for 74 grants from 47 PIs. Comments were reviewed to identify common themes which were then used to develop common cause categories for technology development stopping. Each grant was binned into at least one category and could be binned into any number of categories.

The most common reason mentioned by PIs for stopping the development of their technologies was that no additional development was needed as the technology was fully matured or had transitioned to a modified version (Fig. 27). Only two grants with these comments had not been infused. The next most common reason mentioned was NASA Decision Making/Policy, usually due to follow-on proposals not being selected for funding but also due to the technology being considered too risky for a balloon flight, a lack of mission opportunities, or the technology not being a programmatic priority.

Other reasons that PIs mentioned for stopping development were technology development roadblocks such as manufacturing challenges, lack of personnel, interest, or ability to compete with other research groups, insufficient funding, a community preference for competing technologies, and industry market factors.

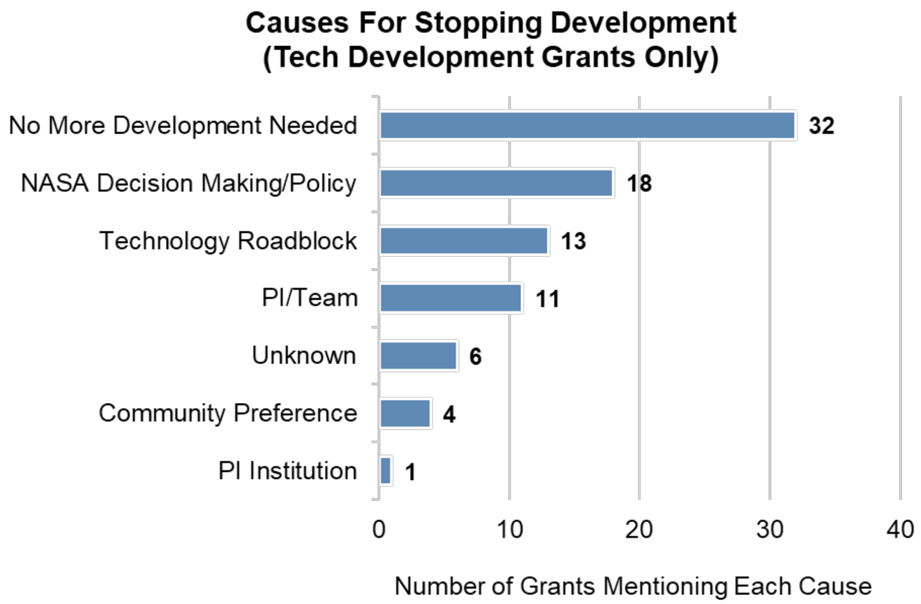


Fig. 27 Number of PI mentions for stopping development of their technologies

4.5 Alternative Benefits of Grants

All surveyed PIs were asked to identify the alternative benefits of their grants besides technology development. This resulted in comments for 466 grants from 201 PIs. As with other comments in the survey, PIs' responses were reviewed to identify common themes. Each grant was then binned into one or more themes.

Most PIs identified multiple alternative benefits of their technology development efforts. On average, PIs listed 2.3 alternative benefits per grant. 27 grants did not have any alternative benefits listed, but most of these 27 grants were still ongoing or had not yet started. Only 5 grants from 2015 or earlier did not have any benefits listed besides technology development.

PIs identified a wide range of alternative benefits from their technology development efforts. The most common alternative benefits mentioned were publications and student or staff development (Fig. 28). Other benefits included infrastructure development, non-flight applications of the developed technologies, development of supporting technologies and software, collaborations with other research groups, and more.

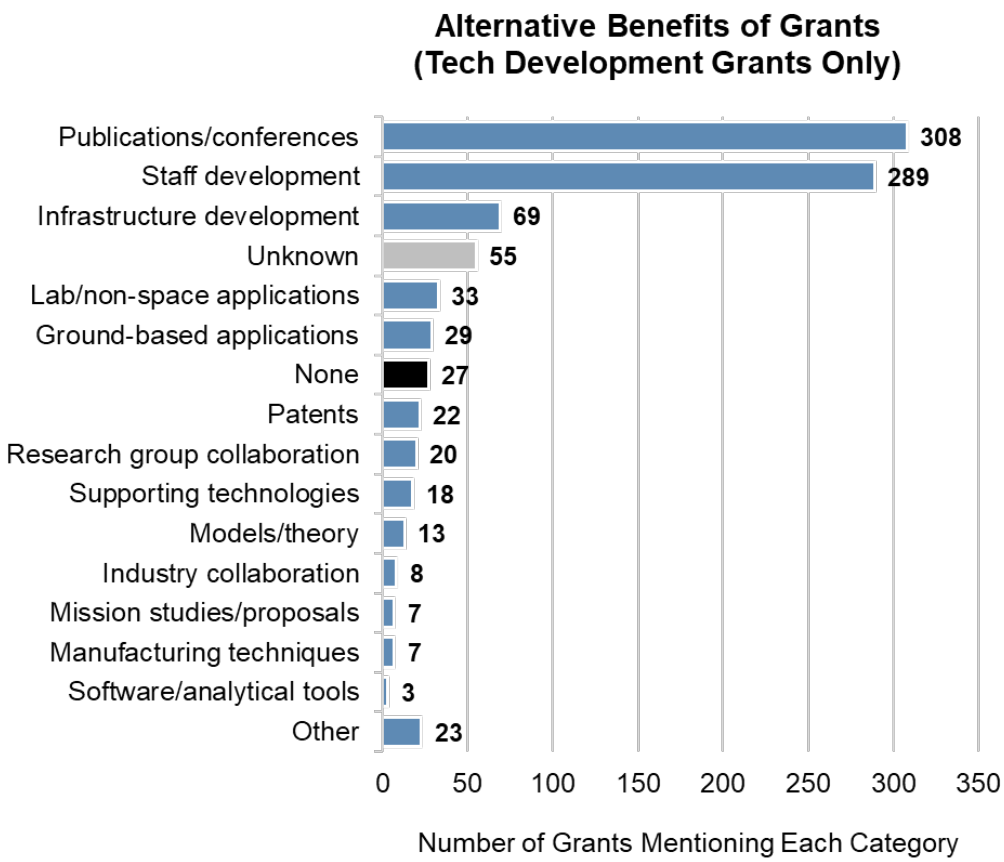


Fig. 28 Alternative (besides technology development) benefits of technology development grants

In many cases, PIs that mentioned staff development as a benefit of their grant efforts included additional details. These details were used to conduct a deeper investigation into the types of students and staff supported by technology development grants (Fig. 29). Grants were most likely to support graduate students, followed by postdoctoral and early career staff. Grants also supported undergraduate students, mid- to late-career staff, and interns. Many grants supported multiple students/staff each.

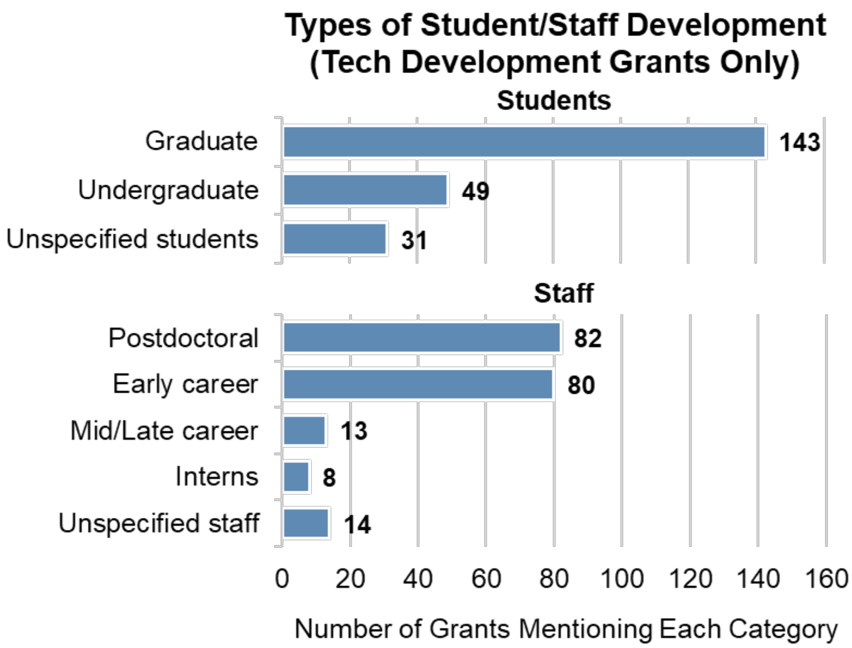


Fig. 29 Details of staff/student types benefiting from technology development grants

4.6 Alternative Funding Sources of Grant Efforts

All surveyed PIs were asked to identify additional funding sources used to develop their technologies. As shown in Fig. 30, most grants (63%) contributed to technologies that required multiple funding sources. Most other funding sources used were additional APD grants (Fig. 31), but internal research and development (IRAD) funding as well as funding from other government agencies, foundations, and other NASA divisions were also widely used.

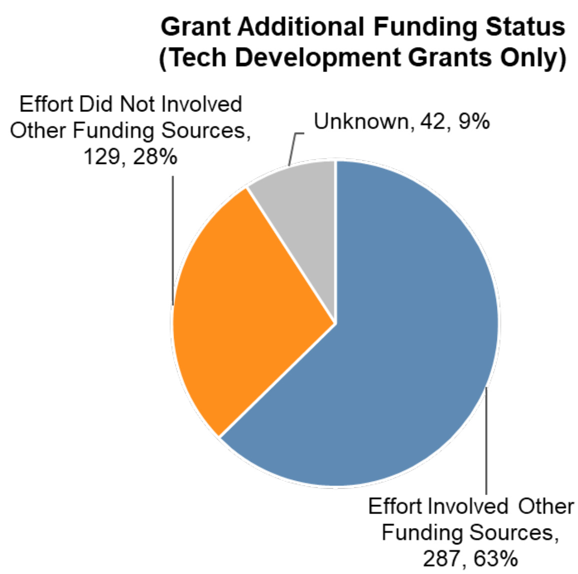


Fig. 30 Additional funding status of technology development grants

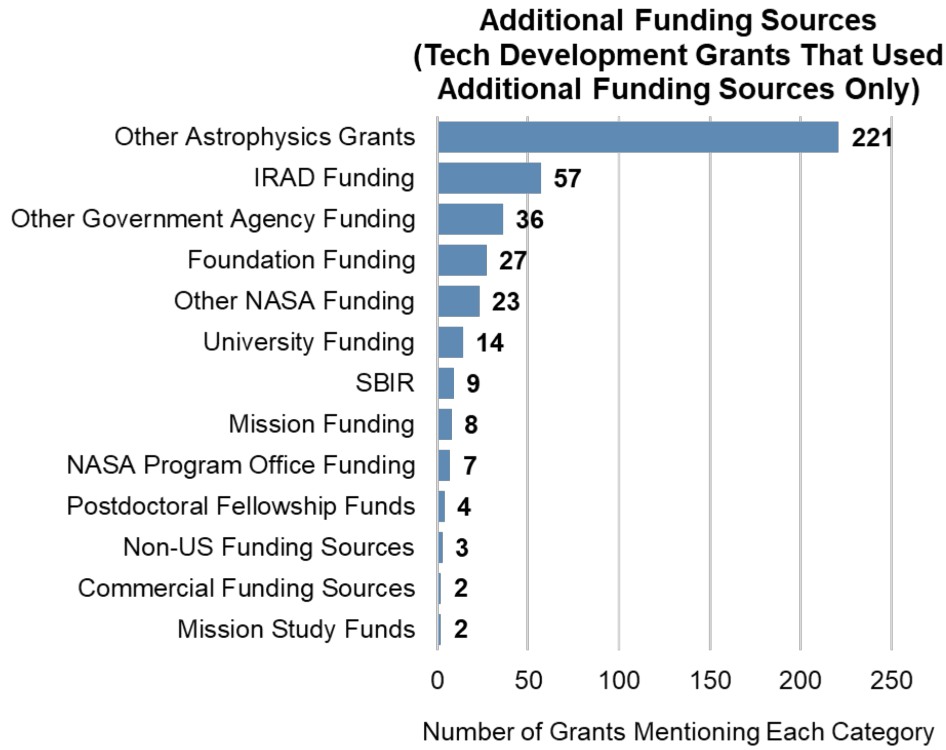


Fig. 31 Additional funding source details

5 Summary & Conclusion

An independent, comprehensive Astrophysics Technology Heritage Study has been conducted for NASA Headquarters APD in effort to understand the overall products received of the grants issued and to understand the impact of the overall portfolio of the grants. The study was organized in three major research areas:

- Grants Database – compilation & analysis of astrophysics technology grants 2009-2020
- Missions Database – space and suborbital missions 2010-Future
- PI Survey – survey of 300+ technology grant recipients 2009-2020

Performance of this study resulted in significant findings including:

- Astrophysics grants have a relatively high (285 of 458 grants, or 62%) infusion rate.
- Majority of Astrophysics missions (76 of 125 missions, or 61%) were funded by at least one Astrophysics grant. This demonstrated that Astrophysics missions for the most part are conceived and implemented within the community of funded PIs, via diverse research grants provided by APD.
- Grants awarded have numerous alternative benefits beyond the primary purpose.
- Lack of opportunity for space missions was the top reason given for technology developed using grants not being infused.

- Most grant recipient organizations received only one grant, but 20 organizations received 61% of all grants (518 of 850 grants)

References

1. **NASA Goddard.** *Astrophysics Technology Development Portfolio.* [Online] [Cited: May 9, 2023.] http://www.astrostrategictech.us/.