UHERO
THE ECONOMIC RESEARCH ORGANIZATION
AT THE UNIVERSITY OF HAWAI‘I

Economic Impact of Astronomy in Hawai‘i: 2019 Update

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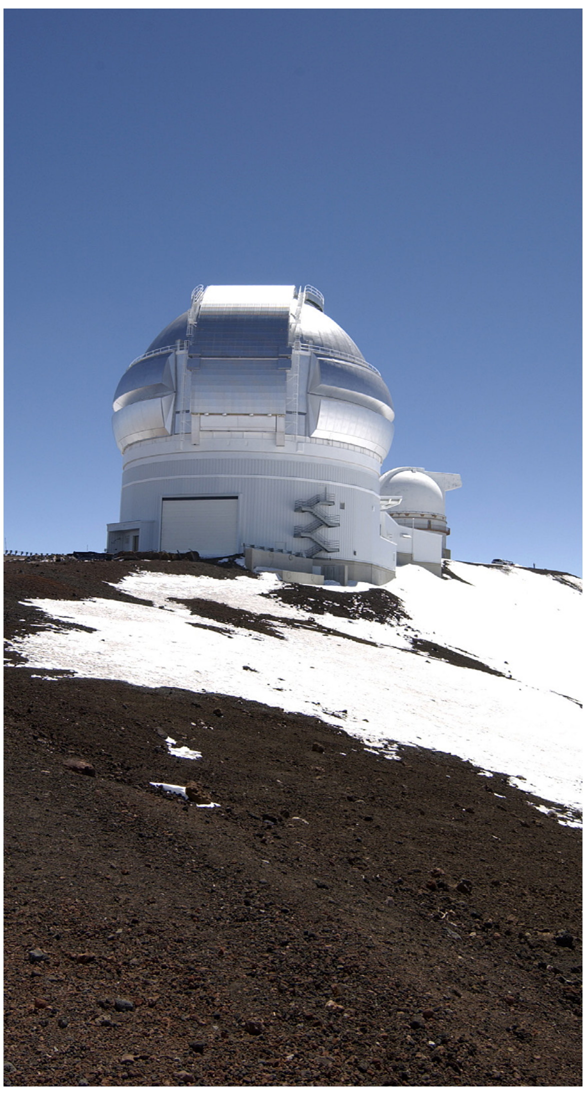

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Economic Impact of Astronomy in Hawaiʻi: 2019 Update

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EXECUTIVE SUMMARY

Hawaiʻi's astronomy sector generates economic activity through direct purchases from local businesses, salaries and wages paid to employees who spend at least part of their income locally, and expenditures by students and visitors. In collaboration with the Institute for Astronomy, UHERO used survey data collected from astronomy related entities throughout the state to estimate the astronomy sector's total economic impact in each of Hawaiʻi's four counties for calendar year 2019. Economic impacts—defined here as the direct, indirect, and induced economic activities generated by the astronomy sector's expenditures in the state—were calculated using the Department of Business, Economic Development, and Tourism's (DBEDT) 2017 Inter-County Input-Output Table, which takes into account the value of goods and services flowing among economic sectors within each county and between counties.

In 2019, local astronomy related expenditures in the state totaled $110.02 million (up from $99.43 million in 2012)[1] with $57.18 million, $35.22 million, $0.28 million, and $17.33 million spent in Hawaiʻi, Honolulu, Kauaʻi, and Maui counties respectively. The $11 million difference in statewide spending can be largely attributed to higher expenditures reported in Honolulu and Maui counties in 2019. Including indirect and induced benefits and adjusting for inter-county feedback effects, the astronomy sector had a total impact on the output of goods and services in the state of $220.95 million (up from $189.47 million in 2012). Astronomy activities also generated $68.05 million in labor income, $10.10 million in state taxes, and 1,313 jobs[2] statewide (compared to $58.99 million, $9.20 million, and 1,394 jobs respectively in 2012).

Astronomy continues to be a sizable and stabilizing source of economic activity. Astronomy output for 2019 was equivalent to 78% of the total farming output statewide, or 21% of the output from the private educational services sector. The astronomy industry also generates knowledge, expertise, and technology benefits for the wider economy, beyond the direct, indirect, and induced impacts accounted for by the standard economic impact methods. These additional impacts are described as spillovers and underpin the case for public investment in research.

INTRODUCTION

In 2014, the Institute for Astronomy (IfA) at the University of Hawaiʻi at Mānoa engaged UHERO to undertake an economic impact assessment of the astronomy sector in Hawaiʻi. UHERO estimated that astronomy contributed $189.47 million to economic activity in 2012, adjusted for 2019 dollars. This report updates that assessment based on 2019 expenditures in the astronomy sector. We examine 2019 expenditure since it is the last full year before the pandemic and better reflects activity in a typical year.

Additional facilities have been developed since 2014. Construction of the National Science Foundation's Daniel K. Inouye Solar Telescope at Haleakalā Observatories began in 2010 with the first images captured in late 2019. It is the largest solar telescope in the world. The IfA's Asteroid Terrestrial-Impact Last Alert System (ATLAS) funded by NASA includes two telescopes based in Hawaiʻi and was completed in 2017. A more detailed description of other astronomy facilities can be found in UHERO's 2014 report on the astronomy sector.

The economic impact of astronomy is assessed on the value of expenditure by participants in the astronomy sector and any flow-on economic impacts. The three main components of the assessment are

1 Values from the previous study (UHERO, 2014) which were reported in 2012 dollars, are adjusted to 2019 dollars to allow for direct comparison with the current study.

2 Although total spending increased in the astronomy sector, the jobs impact declined due to increased labor productivity.

direct, indirect and induced economic impacts. Direct expenditures account for the spending by individuals and organizations in 2019 in the astronomy sector. The source of indirect impacts are expenditures on intermediate goods and services used by the activities included in the direct expenditures. Finally, induced impacts are the astronomy employees' expenditures on household goods and services.

The astronomy industry and research sector in general also generate knowledge, expertise, and technology benefits for the wider economy. These are benefits beyond the direct, indirect, and induced impacts accounted for by the standard economic impact methods used in this report. These additional impacts are described as spillovers and underpin the case for public investment in research. To fully appreciate the economic importance of astronomy, this updated report includes examples of how spillovers from astronomy generate additional economic benefits for Hawai‘i. We especially focus on knowledge spillovers that support future research and local technical manufacturing.

METHODOLOGY AND DATA

The astronomy sector in Hawai‘i generates activity in the local economy through business sales, employee earnings, tax revenues, and job creation. Data on labor earnings and astronomy-related expenditures were collected for three major spending categories: astronomy operations, university students majoring in astronomy, and visiting astronomy researchers. Expenditure types were further classified using the North American Industry Classification System (NAICS) industry descriptions. The total economic activity generated in each county (Hawai‘i, Honolulu, Kaua‘i, and Maui) was then estimated using the 2017 Hawai‘i Inter-County Input-Output (I-O) Model (DBEDT, 2021), which accounts for all sales and purchases made by firms in each sector of the economy, thus capturing the interdependence among industries both within and across counties.

OPERATING EXPENDITURES FOR ASTRONOMY-RELATED ENTITIES

A survey was conducted to obtain information from astronomy-related entities about in-state expenditures for calendar year 2019 (see Appendix). The survey, which was designed in collaboration with the Institute for Astronomy and used for the previous UHERO report on the impact of astronomy in Hawai‘i (UHERO, 2014), included several expenditure categories: salaries and wages, rent on facilities and equipment, capital purchases, supplies, information services, utilities, professional services, repair and maintenance, and construction. Data was collected from mountain-top observatories on Maunakea and Haleakalā, the Center for Maunakea Stewardship, the UH Institute for Astronomy, the UH Hilo Department of Physics and Astronomy, and the ‘Imiloa Astronomy Center. Data in each survey response were organized by county and expenditure category and then assigned to one of the 20 industries used in the I-O model: agriculture, mining and construction, food processing, other manufacturing, transportation, information, utilities, wholesale trade, retail trade, finance and insurance, real estate and rentals, professional services, business services, educational services, health services, arts and entertainment, accomodation, eating and drinking, other services, and government. Individual responses were then aggregated for each of the 80 county-industry combinations.

To properly estimate the economic impacts of astronomy expenditures, the spending data from the survey must be converted from the retail level to the producer level because transactions in the I-O model are valued at producer prices. Retail level expenditures on goods and services were converted to producer level expenditures for each I-O sector by subtracting sector-specific retail, wholesale, and transportation margins

(Appendix C in DBEDT, 2020). The subtracted margins were then aggregated and added back to each of their respective sectors. For example, the transportation margins subtracted from the expenditure totals for each of the other 19 sectors were summed and added to the expenditure total for the transportation sector before the economic impacts were calculated.

As noted previously, the survey included specific questions regarding salaries and wages, employee benefits, retirement contributions, and FICA taxes. Expenditures on labor were separated from other spending because a substantial portion of labor earnings are injected back into the economy in the form of household purchases of goods and services. These are therefore treated as an additional producing sector in the economy with its own unique set of assumptions regarding the share allocated to in-state versus out-of state spending, as well as a different set of economic multipliers. Net labor earnings were calculated for each county as the sum of wages, salaries, and benefits, less FICA taxes. Net earnings were further adjusted in each county for out-of-state imports (15.2% for Hawaiʻi, 15.3% for Honolulu, 15.3% for Kauaʻi, and 15.3% for Maui) and within-state imports (23.5% for Hawaiʻi, 5.8% for Honolulu, 21.9% for Kauaʻi, and 26.0% for Maui) based on estimates reported in the 2017 Hawaiʻi Inter-County Input-Output Study (Table A-5 in DBEDT, 2021). Within-state imports for each county were redistributed across the 20 I-O industries using fixed personal consumption expenditure (PCE) shares that were calculated from the 2017 Hawaiʻi Inter-County I-O Transaction Table. For example, of the estimated $43.5 million in net labor earnings reported for Hawaiʻi County in 2019, the roughly $8.8 million attributed to within-state imports from Honolulu County were redistributed to the 20 I-O industries in Honolulu using the fixed PCE shares calculated from the 2017 transaction table.

UNIVERSITY STUDENT EXPENDITURES

There are four astronomy degree programs (UH Mānoa BA, MS, PhD; UH Hilo BS) and one astrophysics degree program (UH Mānoa BS) in the state of Hawaiʻi. Fall 2019 enrollment data was obtained for each program from the UH Institutional Research Analysis and Planning Office (data.hawaii.edu). Because conducting a survey on student expenditures was outside the scope of this study, estimates were based on the average spending per student in each county that was reported in a recent study examining the economic impact of the University of Hawaiʻi System (UHERO, 2021). Total student expenditures was calculated by multiplying the number of students in each county, 101 in Honolulu and 32 in Hawaiʻi, by the corresponding average annual spending by a UH student in that county, and then distributing that spending across the 20 I-O industries.

VISITING RESEARCHER EXPENDITURES

Ideally our analysis would include tourist visitors who spent a portion of their vacation participating in astronomy-related activities. In fact, the Center for Maunakea Stewardship estimated that nearly 30,000 vehicles and over 70,000 visitors passed through the Maunakea visitor station in 2019 alone. However, identifying the proportion of total vacation spending attributed specifically to astronomy activities would be challenging, given that most tourists do not come to Hawaiʻi specifically to visit observatories or other astronomy facilities. Instead, visitor expenditures were calculated only for individuals who came to Hawaiʻi to work at astronomy facilities.

Data was collected by the IfA on the number of visiting astronomy researchers and average duration of stay in 2019. We then calculated total visitor spending in each county by multiplying the total number of person-days by the corresponding average personal daily expenditures in 2019 for visitors in that county (HTA, 2020). Total visitor expenditures were adjusted in each county for out-of-state imports (6.6% for all counties) and within-state imports (10.5% for Hawai'i, 0.7% for Honolulu, 17.5% for Kaua'i, and 15.8% for Maui), based on estimates presented in the 2017 Hawai'i Inter-County Input-Output Study (Table A-6 in DBEDT, 2021). Within-state imports for each county were redistributed across the 20 I-O industries using fixed visitor expenditure (VE) shares that were calculated from the 2017 Hawai'i Inter-County I-O Transaction Table. For example, of the estimated $1.01 million spent by visiting astronomy researchers in Hawai'i County in 2019, the nearly $100,000 attributed to within-state imports from Honolulu County were redistributed to the 20 I-O industries in Honolulu using the fixed VE shares calculated from the 2017 transaction table.

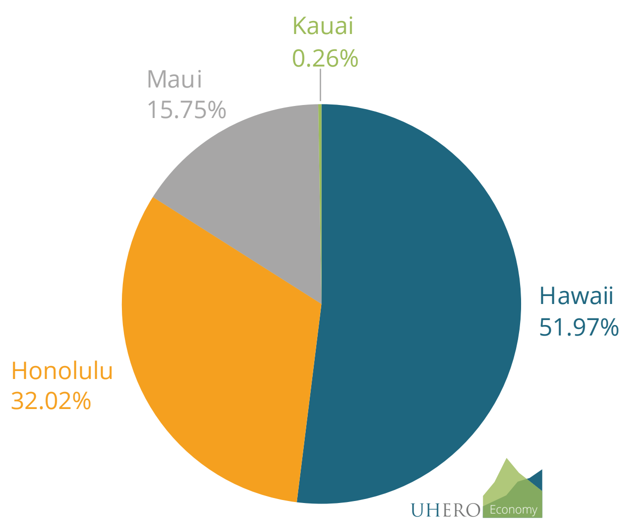
TOTAL IN-STATE EXPENDITURES ON ASTRONOMY

Total local astronomy expenditures were calculated for each county as the sum of spending on astronomy facility operations, personal consumption expenditures, spending by university students, and visiting researcher expenditures, all adjusted for out-of-state and in-state imports, as detailed in the previous sections. Local expenditures totaled $57.18, $35.22, $17.33, and $0.28 million in Hawai'i, Honolulu, Maui, and Kaua'i counties respectively (Table 1). Of the $110.02 million in total statewide astronomy expenditures, Hawai'i county accounted for more than half, while Honolulu contributed nearly one third (Figure 1).

TABLE 1. TOTAL ASTRONOMY-RELATED LOCAL EXPENDITURES BY COUNTY

County	Expenditures (millions of 2019 dollars)
Hawai'i	57.18
Honolulu	35.22
Maui	17.33
Kaua'i	0.28
Total	110.02

FIGURE 1. SHARE OF ASTRONOMY-RELATED LOCAL EXPENDITURES BY COUNTY



ECONOMIC IMPACT CALCULATIONS

Inter-county type II multipliers capture the direct, indirect, and induced impacts per dollar of spending in each of the 20 I-O sectors. The advantage of using an inter-county model over a state-level I-O model is that the former accounts for both flows of goods and services within each county and between counties, thereby capturing feedback effects. For example, when a new economic activity in Hawaiʻi County increases an industry's final demand and the produced output in that county, new flows of goods and services are required from the other three counties (Honolulu, Kauaʻi and Maui), resulting in increased output in those counties as well. The increased production in those counties might consequently create new demand for goods and services produced in Hawaiʻi County (e.g., via purchase of production inputs) - a feedback effect. To ensure that our results included direct, indirect, and induced effects, as well as inter-county feedback effects, type II inter-county total requirements tables[3] were used to estimate economic impacts for each county in terms of output, earnings, state taxes, and jobs. Each total requirements table was multiplied by corresponding local expenditures for each county-industry pair, resulting in four impact tables. For a given impact category (e.g., output), total impact for a specific county was calculated by summing over all industries in that county. Total impact in a specific industry was calculated by summing over all counties for that industry.[4]

ASTRONOMY'S IMPACT ON HAWAIʻI'S ECONOMY

In calendar year 2019, astronomy-related expenditures totaled $110.02 million in Hawaiʻi (up from $99.43 million in 2012 after adjusting for inflation). Including indirect and induced benefits from these activities and adjusting for inter-county feedback effects, the astronomy sector had a total impact on the output of goods and services in the state of $220.95 million (up from $189.47 million in 2012). As Table 2 shows, astronomy activities also generated $68.05 million in labor income, $10.10 million in state taxes, and 1,313 jobs statewide (compared to $58.99 million, $9.20 million, and 1,394 jobs respectively in 2012). Note that although total spending increased in the astronomy sector from 2012 to 2019, the job impact declined due to rising labor productivity over the same period.

Over half of local astronomy-related spending occurred in Hawaiʻi County. The $57.18 million of expenditures in Hawaiʻi County alone generated $101.68 million in local business sales (or 46.02% of the total impact on business sales statewide), $28.52 million in employee earnings (41.92% of the total earnings impact), $4.08 million in state tax revenue (40.40% of the total tax impact), and 611 jobs (46.51% of the total jobs impact). Impacts for the other three counties are summarized in Table 2.

TABLE 2. ECONOMIC IMPACTS OF ASTRONOMY-RELATED LOCAL EXPENDITURES BY COUNTY

County	Output	Earnings	State Taxes	Jobs
		(millions of 2019 dollars)		(#)
Hawaiʻi	101.68	28.52	4.08	611
Honolulu	86.96	30.42	4.85	517
Kauaʻi	1.59	0.41	0.06	9
Maui	30.72	8.69	1.11	176
State	220.95	68.05	10.10	1,313

3 A total requirements table is a matrix of coefficients representing the sum of direct and indirect purchases required to produce one dollar of output, one dollar of earnings, one dollar of state taxes, or one job.

4 Additional details on the methods used for the impact calculations, including mathematical derivations, can be found in Appendix B of the previous UHERO report on the economic impact of astronomy in Hawaiʻi (UHERO, 2014), as well as in the 2017 Hawaiʻi Inter-County Input-Output Study (DBEDT, 2021).

Table 3 provides a breakdown of initial astronomy-related local spending and the resulting economic impacts by industry for the state of Hawai‘i. The real estate and rentals industry (18.4%) and the professional services industry (11.3%) accounted for the largest shares of direct spending; all other industries contributed less than 9% each. However, the consequent economic impacts were not proportional to the initial direct spending due to structural differences in the way each of the 20 industries allocates spending within and across the four counties.

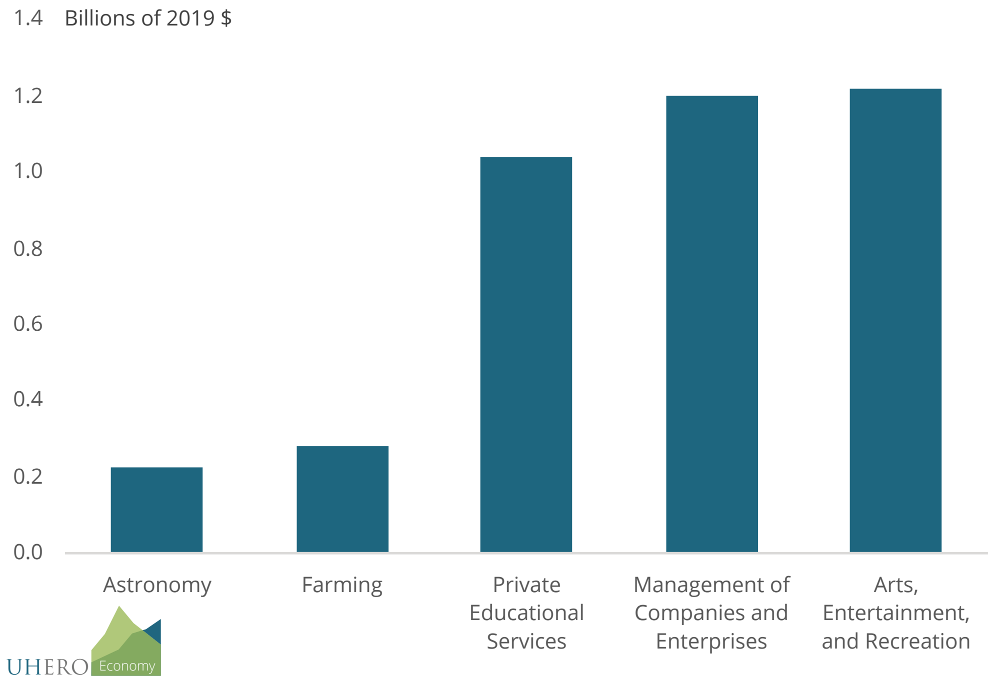
TABLE 3. EXPENDITURES AND ECONOMIC IMPACT SHARES (%) AMONG INDUSTRIES

Industry	Local Expenditures	Output	Earnings	State Taxes	Jobs
Agriculture	0.3	0.6	0.8	0.4	2.1
Mining and construction	3.4	3.1	4.3	4.4	2.6
Food processing	0.6	0.9	0.5	0.4	0.7
Other manufacturing	4.8	3.8	2.4	1.1	2.8
Transportation	3.1	4.0	3.6	2.9	3.2
Information	4.3	4.3	2.9	3.8	1.7
Utilities	6.2	4.4	3.2	3.5	1.1
Wholesale trade	8.8	6.1	6.4	2.7	5.3
Retail trade	7.4	6.0	7.2	8.2	10.0
Finance and insurance	3.3	4.0	3.4	4.4	3.4
Real estate and rentals	18.4	22.1	4.2	14.9	6.0
Professional services	11.3	7.9	12.2	11.3	11.9
Business services	2.7	5.5	9.2	8.3	10.7
Educational services	2.0	1.4	3.4	2.5	4.4
Health services	8.6	7.5	11.7	10.3	9.7
Arts and entertainment	0.7	0.6	1.1	0.9	1.8
Accommodation	2.5	3.8	3.3	8.3	2.6
Eating and drinking	3.0	3.4	4.3	4.8	6.4
Other services	5.6	6.8	7.2	4.4	8.4
Government	2.9	3.6	8.7	2.5	5.2

ASTRONOMY: A SIZABLE AND STABILIZING SOURCE OF ECONOMIC ACTIVITY IN HAWAI‘I

Astronomy continues to be a sizable and stabilizing source of economic activity. Figure 2 shows the astronomy sector’s contribution to Hawai‘i’s economy compared with other similar sized sectors. Astronomy output for 2019 was equivalent to 78% of the total farming output statewide, or 21% of the output from the private educational services sector.

FIGURE 2. A COMPARISON OF ASTRONOMY OUTPUT TO OTHER SECTORS IN THE ECONOMY



SPILLOVERS FROM ASTRONOMY IN HAWAIʻI

The astronomy industry and research sector in general also generate knowledge, expertise, and technology benefits for the wider economy. These are benefits beyond the direct, indirect, and induced impacts accounted for by the standard economic impact methods in this report. These additional impacts are described as spillovers and underpin the case for public investment in research. To fully appreciate the economic importance of astronomy, this section describes how spillovers from astronomy generate economic benefits for Hawaiʻi.

WHAT IS A SPILLOVER?

The term ‘spillover’ refers to any additional benefits and costs that are not accounted for by the people choosing to undertake the activity. Since they are not accounted for in standard decision-making processes, they are external and also referred to as “externalities”. Such spillovers include new businesses, related research projects, graduates with transferable skills, the value of economic activity beyond market prices, and other related activities.

TYPES OF SPILLOVERS

For the purpose of this report, we categorize spillovers by three main types: Market spillovers, network spillovers, and knowledge spillovers.

MARKET SPILLOVERS

Market spillovers refer to value generated by market-based mechanisms that are not captured by the people or organizations producing the product or undertaking the activity. In particular it refers to the value that transfers to consumers who value economic production more than its price, known as consumer surplus. In the astronomy sector the consumers are the funding bodies that pay for its activities. In the case of research, much of this is publicly funded, and so its public benefit that justifies public funding comes from knowledge spillovers as discussed below, rather than a traditional consumer surplus. For privately funded activities, the consumer surplus is the share of profit made by those businesses that can be attributed to their working with the astronomy sector.

NETWORK SPILLOVERS

Network spillovers occur when the economic activity in one sector generates additional value in another sector. These are positive externalities because their benefit is not accounted for by the people and organizations directly involved. The existence of network spillovers creates a coordination problem, in that the later sector might not invest until it can be sure that the former sector is going to undertake its activity. Tourists who extend their vacation or spend money to visit astronomy facilities and use access roads are a network spillover that is not included in the economic impact analysis above.

KNOWLEDGE SPILLOVERS

The case for public investment in research is based on the evidence that there are significant *positive* externalities known as “knowledge spillovers”. This refers to the wider benefits of knowledge when it is used for some other purpose beyond the research and development program that originally discovered or developed that new knowledge. In particular, new innovations build on decades of previous research, but only the new innovation itself generates a commercial return. Without government support, private businesses will not account for the wider benefits of knowledge spillovers from research and so will under-invest in research activities. Actual investment in R&D is estimated to be between one quarter and one half of its optimal level, after accounting for knowledge spillovers (Jones and Williams, 1998).[5] This implies a significant market failure that justifies substantial public investment in research activities. While the astronomy sector generates spillovers in each of the three categories, in this report we focus primarily on examples of knowledge spillovers.

Knowledge spillovers can be further split into three categories: *Education*, *business*, and *research*. Education knowledge spillovers are knowledge learned in the education and training activities undertaken by students and workers in the astronomy sector in Hawai‘i that are transferable to other industries and places. Business knowledge spillovers are the expertise and capabilities of businesses—developed in the process of their work for the astronomy sector—that are transferable to production in other sectors. Research knowledge spillovers are the knowledge generated by the research programs in the astronomy sector that lead to further research projects in the future. These are new research projects that were not already conceived of at the time of the original research program, and that would not have occurred without the originating research. This also includes research undertaken alongside astronomy as part of its stewardship role to reduce their negative impact on the environments where they operate. Such research would not otherwise occur without the cooperation of astronomy researchers.

Knowledge spillovers have the potential to *eventually* lead to commercialization of new innovations and businesses that would not be able to occur without the discovery of new knowledge and development of research programs. Therefore the benefits of knowledge spillovers extend well into the future and generate benefits that are not yet known. Some of these spillovers occur within the astronomy sector and are measured above in the standard economic impact analysis if they occurred in 2019. But the benefits of spillovers occur over many years and decades, so the spillovers included in current economic activity are a result of activities that occurred over previous years and even decades. Similarly, expenditure included in the current economic impact analysis may have spillover benefits that will not be known for many years or even decades into the

5 For additional discussion, see Jones and Summers (2020).

future. This implies that the standard measure of economic impact from research in any one year will under-estimate the true economic value of research.

TRANSMISSION OF KNOWLEDGE SPILLOVERS AND THE IMPORTANCE OF LOCATION

Knowledge can be separated into two categories: Codified knowledge; and tacit knowledge.

CODIFIED KNOWLEDGE

Codified knowledge refers to ideas that can be formally recorded in some manner and transferred easily between people or places. Blueprints, or a mathematical formula are codified knowledge. Modern information communications technology (ICT) can transmit codified knowledge around the world in seconds. As a result, codified knowledge spillovers can transfer easily from one location to another.

TACIT KNOWLEDGE

Tacit knowledge cannot be formally recorded and transferred easily. It is the subtle knowledge that people learn by experience, by intuition, by teamwork, or by face-to-face interaction. Tacit knowledge is built around interpersonal contact, trust, and collections of routines that are embodied in individual firms and localized networks. Tacit knowledge is considered the primary reason for the competitive advantage of particular firms or regions. Tacit knowledge may not even be explicitly recognized by the people who possess it.

Mechanisms that transmit tacit knowledge spillovers are therefore typically spatial, in that there is a greater local spillover that diminishes with distance. These mechanisms include labor mobility, worker interaction, exchange, and commercialization. These mechanisms are affected by geography: Workers typically shift jobs within the same local labor market area; workers interact more frequently with colleagues and friends in the same city; Foreign Direct Investment, trade and international collaborations are more frequent between nearby countries; and commercialization benefits arise within a business itself. Therefore, knowledge spillovers are greater in closer spatial proximity to where the activity takes place. Such spaces are not only defined by geographic distance, but by connectivity, such as transportation and communication links. For example, even if Hawaiʻi is geographically closer to other islands in the Pacific, there will be greater transmission of tacit knowledge between Hawaiʻi and the mainland United States due to much more frequent transport and communication.

The spatial nature of knowledge spillovers explains the intense clustering of science and technology activities in specific places around the world. Tacit knowledge spillovers imply significant <u>local</u> economic benefits for a city or state that hosts a research sector such as astronomy.

MOBILITY

Since tacit knowledge spillovers are local, the location and mobility of a research sector determines the location of the economic benefits of knowledge spillovers. For some sectors, there is no local reason why the sector exists in its present location other than a historical accident. Businesses in these sectors can be mobile if it emerges that a location has desirable characteristics, such as a tax credit that allows them to shift location. The more intense the knowledge spillovers between related businesses, the more likely these firms are to cluster in one place. For example, ICT start-up businesses in Hawaiʻi may be likely to move to the Bay Area in California relatively early in their development to access tacit knowledge spillovers that are only found in and around Silicon Valley. If a location can curate an initial specialized cluster of firms with inter-dependent knowledge spillovers, then it can continue to host that industry for a long time because each firm prefers to remain in their location.

For other sectors, a local resource endowment, that is a key factor of production, determines the location of the sector. These industries are much less mobile because they are bound to the location of that factor of production. These are important sectors for economic development in smaller and more isolated economies because these sectors are able to remain in that location for a long time and are at less risk of leaving, in spite of the geographic isolation that would typically push knowledge intensive industries to cluster in a more accessible location. This characteristic explains the intense clustering of the visitor industry in Hawaiʻi that relies on Hawaiʻi's climate and scenery as an important factor of production to attract visitors.

The astronomy sector is closely tied to Hawaiʻi's geographic location because it requires a factor of production that is uniquely found in Hawaiʻi: locations possessing the ideal combinations of environmental and geographical factors for siting locations of high-powered telescopes, including high-elevation remote mountain tops, pristine air quality, and low light pollution. Therefore, it is a sector that is unlikely to relocate anywhere else. This also means that it is an important research sector to maintain, because the industry, its spillovers, and its economic benefits are more likely to remain in Hawaiʻi. If this sector were to decline in Hawaiʻi, it would be unlikely to achieve the same economic benefits elsewhere. Nonetheless, global spillovers from the astronomy sector in Hawaiʻi also provide important economic benefits to people around the world.

CASE STUDIES OF SPILLOVERS IN ASTRONOMY

Spillovers are difficult to measure since they may take many years or even decades to become apparent. Furthermore, the spillover link from the original research activity to other economic activity is not always clear. Explaining and measuring the entire range of spillovers from astronomy is beyond the scope of this report. Instead, a number of examples are described below to demonstrate the economic importance of spillovers from astronomy, particularly in the knowledge spillovers category.

NETWORK SPILLOVERS

The telescopes hosted on Maunakea and Haleakalā require access roads, communications equipment, and emergency services. However, astronomers are not the only ones who use this infrastructure and services. As a result, visitors can make use of the infrastructure and related services to undertake tourism activities such as hiking and sightseeing. Therefore, the economic activity that results from visitors coming to Hawaiʻi or extending their stay in order to visit Maunakea and Haleakalā are a spillover from the astronomy sector that is not captured by the standard economic impact analysis. For example, as noted previously, the Center for Maunakea Stewardship estimated that nearly 30,000 vehicles and over 70,000 visitors passed through the Maunakea visitor station in 2019, visitors who might not have participated in tourism activities on Maunakea were it not for the infrastructure and services maintained by the local astronomy industry.

Similarly, building, maintenance, and stewardship of the astronomical observatory sites has enabled and required other activities that are not directly related to astronomy itself. For example this includes the building of a visitor center, communications infrastructure and emergency response facilities. Sometimes network spillovers are entirely unexpected such as the discovery of a lost colony of Hawaiian petrels (in Hawaiian, ʻuaʻu) on Maunakea and the discovery of populations of Wēkiu bugs on other volcanic cones on Hawaiʻi Island. Wēkiu bugs were thought to be almost extinct, but were removed from the endangered species list in 2011.

KNOWLEDGE SPILLOVERS

EDUCATION

The astronomy sector in Hawaiʻi plays an important role in astronomy education. Education passes both tacit and codified knowledge spillovers to new people, who use their knowledge and skills in their subsequent work after they graduate. The economic benefits of UH Astronomy graduates who work in astronomy in Hawaiʻi are already included in the direct economic benefits of the astronomy sector, measured by their wages. But the economic benefits of graduates who transfer their skills to jobs in other sectors or new places, also provide economic benefits, or spillovers, that are not counted by traditional economic impact analysis. The IfA has graduates working at NASA, defining science policy in Washington, and in Astronomy leadership roles outside of Hawaiʻi. In addition, there are graduates and former employees who remain in Hawaiʻi but can transfer their skills and knowledge to non-astronomy applications.

One example of knowledge spillovers in education, beyond the astronomy sector in Hawaiʻi, is *Dr Kelly Blumenthal*, Deputy Director of the International Astronomy Union (IAU) Office for Astronomy Outreach, based in Japan. Dr Blumenthal was a graduate student in Astronomy at the University of Hawaiʻi at Mānoa and now works closely with astronomers around the world to facilitate public engagement with astronomy. In particular, she emphasizes the importance of the communication skills she learned while working and researching astronomy in Hawaiʻi. These skills are an example of tacit knowledge—that was only transferred to her with experience working in person in the astronomy sector in Hawaiʻi—that now provides economic benefits in the form of her work for the IAU in locations around the world. Furthermore, the connections to Hawaiʻi, with graduate supervisors and with the network developed while studying in Hawaiʻi, provide for continued knowledge spillovers from the astronomy sector in Hawaiʻi to international stakeholders in astronomy outreach.

Skills and knowledge learned and acquired in astronomy generate spillovers to sectors outside of astronomy. Astronomy is a sophisticated and complex field that builds from many fundamental science skills. *Oceanit*, a research and engineering laboratory and consultancy in Honolulu, employs a number of astronomy graduates, PhDs and even former IfA employees. These employees work in fields that include astronomy, but also systems biology, artificial intelligence, quantum materials, lasers and radio frequency communications. Each of these subjects has foundational science that integrates into and utilizes astronomy education and research. New innovations developed at Oceanit build on the prior fields of study that transfer or translate to new endeavors. This spillover into new technologies helps to support a more diverse economy in Hawaiʻi.

LOCAL BUSINESSES

The astronomy sector requires very precise and complex machinery and equipment. The technical nature and uniqueness of this equipment requires a close collaboration between astronomers and machinists to understand the specific requirements. Much of this collaboration is tacit, in that it requires trust, inspection, face-to-face interaction and hands-on quality assurance. Therefore, the IfA even hosts their own machine shop for building scientific instruments that go on the telescopes, extensive computing facilities, and remote observing facilities. In addition, some machinery can be sourced from other local machine shops or sourced interstate. The local sourcing of equipment emphasizes how tacit knowledge is a key factor of production for this type of manufacturing such that much of this manufacturing activity can only be hosted alongside astronomers here in Hawaiʻi.

The manufacture of this equipment is captured in the economic impact analysis by the expenditures of astronomy organizations. But, the people and firms involved in precision manufacturing for astronomy develop technical skills and capabilities that meet the needs of astronomers, and that are also useful for manufacturing equipment outside of astronomy. By hosting an astronomy research sector in Hawai‘i—which provides key customers and knowledge for these businesses—Hawai‘i is also able to host manufacturing capabilities that wouldn’t otherwise exist in Hawai‘i. As a result, Hawai‘i hosts a small, specialized precision manufacturing industry.[6] This spillover is a wider economic benefit of astronomy in Hawai‘i that is not captured in the standard economic impact analysis.

An important aspect of this precision manufacturing industry is that the products are typically one-of-a-kind, or involve very few units. This means that there are low economies of scale, since producing more output typically requires multiple outputs, rather than multiple units of the same product. Industries with economies of scale generate lower costs as the size of the production run expands or as the size of the business expands. These industries are typically located in larger cities, where there are more customers, since this minimizes the costs of transporting products and interacting with customers. Due to Hawai‘i’s isolation, manufacturing with economies of scale is not a typical activity in Hawai‘i. So the ability to host a manufacturing industry without economies of scale is a natural fit for Hawai‘i, but it probably wouldn’t have emerged in Hawai‘i without the astronomy sector to provide an anchor customer base.

One example of a local precision manufacturer for astronomy, that also produces for other sectors, is Bear Machinery, a machine shop based in Kāne‘ohe, O‘ahu. Bear Machinery uses Computer Numerically Controlled (CNC) machines for the manufacturing and fabrication of parts and subassemblies for specialized equipment and machinery. Digitally automated CNC machines use various types of cutting tools to precisely turn/machine through materials to create complex geometric shapes to the desired configuration and tolerance. They specialize in machining expertise, modern equipment and up-to-date software, and work with various types of materials including aluminum, stainless steel, brass, molybdenum, inconel, titanium and plastics. By hosting this complex capability for manufacturing specialized equipment for the astronomy sector, Bear Machinery is also able to manufacture specialized equipment for businesses outside of the astronomy sector. Sectors outside of astronomy that benefit from Bear Machinery’s capabilities include aerospace, oceanography, health care and the U.S. military. Specific customers include Boeing, HSI Electric Boat and Beachside Lighting.

Another example of a manufacturer in Hawai‘i that developed as a spillover from astronomy research in Hawai‘i is *Hawaii Aerospace*. Gerard Lupino was a professor at the University of Hawai‘i at Mānoa and began an instrumentation company, GL Scientific, in partnership with Ryan Bradley. After Gerard Lupino passed away, the company rebranded as Hawai‘i Aerospace. Based in Pālolo Valley on O‘ahu, they host a number of specialized milling machines and equipment. The company builds on knowledge spillovers from the astronomy sector to produce instrumentation and provide engineering support for both ground-based and space-based astronomy. While some of this activity would be included in the economic impact analysis, some is for clients outside of Hawai‘i or beyond ground-based astronomy itself. Most of their work is for one-off designs, though there is some recurring production for Teledyne Technologies. Other customers include NASA-GSFC, NASA-JPL, NASA-Marshall, Raytheon, MIT, MIT Lincoln Lab, UH-Hilo, UH-Mānoa and Mauna Kea Infrared.

Similarly, *Mauna Kea Infrared LLC* (MKIR) is an instrumentation manufacturer based in Hilo on Hawai‘i Island, established by a former University of Hawai‘i employee, Doug Toomey. MKIR specializes in the design,

6 Some of the NAICS six-digit industries include 332710-Machine Shop; 332721-Precision Turned Manufacturing; 332999-Fabricated Metal Manufacturing; 333298-Industrial Machinery Manufacturing; 333999-General Machinery Manufacturing; 336999-Transportation Machinery Manufacturing; and 339999-Miscellaneous Manufacturing, which all include manufacturing outside of Astronomy.

construction and testing of custom electro-optical research equipment, primarily infrared instruments for the professional astronomical community. The business was started in 1985 as a side project and became Doug's full-time business from 2001. Spin-off businesses from academic research is an important spillover mechanism to shift research knowledge from universities to commercial applications. MKIR has a 3,500 square foot building equipped with instrument design, assembly and testing areas. This includes a 25 foot high ceiling cleanroom for instrument assembly with a 5 ton overhead crane. They have worked on infrared instruments that cover the 1 to 20 micron range with an emphasis on 1-5 microns. They have also worked on numerous visible wavelength instruments. Their most ambitious project to date was a dual channel coronagraphic camera with an adaptive optics front end for the Gemini 8 meter telescope in Chile. This $4 million camera that is about the size of a SUV is presently being used to search for planets around other stars. They have also provided instrumentation for other telescopes in India and Russia. Importantly, the knowledge used to produce instruments for astronomical imaging has also been used for a few non-astronomy projects including imaging the human iris at a distance of 10 meters and contributing to the SPIR phase one of a ballistic missile sensor. One factor that enables MKIR to be located in Hawai'i, or even requires a Hawai'i location, is the need for short-term local experts to join collaborations with MKIR. The cluster of experts associated with astronomy and instrumentation and based in Hawai'i are a critical resource.

RESEARCH

Research knowledge spillovers occur when the knowledge and discoveries of previous research are useful to new research. The IfA has conducted a number of research projects that have led to and continue to lead to subsequent research including new external funding brought to the University of Hawai'i. These dollar amounts are included in the standard economic impact analysis but only if they occurred in 2019. But the benefits of spillovers occur over many years, so the spillovers included in current economic activity are a result of research projects that occurred over previous years and even decades. Similarly, the research project expenditure included in the current economic impact analysis may have benefits that will not be known for many years into the future. This implies that the standard measure of economic impact from research in any one year will under-estimate the true economic value of research. Here we describe a few examples of past research projects that generated spillovers for subsequent research.

INFRARED CONTROLLER ELECTRONICS

The IfA has developed infrared controller electronics over many years. The first generation of infrared controller electronics was a project funded by the National Science Foundation for the NASA infrared telescope facility in 1992. The technology developed for that project generated spillovers to subsequently developing infrared controller electronics for the W.M. Keck Observatory as part of a project by NASA's Jet Propulsion Laboratory at Caltech in 1993; and for the STELIRCam Infrared Camera as part of a project for the Smithsonian Astrophysical Observatory in 1995.

Subsequent projects continued to build on this research. The second generation of infrared controller electronics were developed in 1998 again funded by the National Science Foundation for the NASA infrared telescope facility. Several more projects to develop second generation controllers followed, building on knowledge spillovers from previous projects. Infrared controller electronics for Astrocam were installed in the U.S. Naval Observatory in Flagstaff, AZ in 1999; in the Subaru Telescope of the National Astronomical Observatory of Japan at Maunakea, HI in 1999; and the Stratospheric Observatory for Infrared Astronomy, a flying observatory in a Boeing 747 that is a joint project between NASA and Deutsches Zentrum für Luft- und Raumfahrt (DLR, the German Space Agency) in 2000. The Redstar3 array controller represents the third generation of infrared controller electronics. It was developed and installed in NASA's Infrared Telescope

Facility in 2002. The project generated knowledge spillovers when this third generation controller was installed in the Gemini South Observatory in Chile, in 2003.

STARGRASP

The Pan-STARRS Giga-Pixel 1 camera was a $4 million project commissioned in 2004 and installed in 2007. At the time the camera was the largest digital camera in the world by number of pixels. It would produce a large astronomical database by making a widefield survey of the sky. The Scalar Topology Architecture of Redundant Gigabit Readout Array Signal Processors (STARGRASP) controller was developed to handle the enormous intensity of information gathered by the camera. A subsequent $4 million Giga-Pixel 2 camera project followed with enhancements that built on knowledge spillovers from the original project.

As a result of the knowledge developed in these two projects, the IfA was commissioned to produce STARGRASP electronics for the Australian National University at the Siding Spring Observatory in New South Wales, Australia. This included producing electronics in 2000, spare electronics in 2020 and acquiring the Intellectual Property for the controller in 2022.

Several more projects followed that built on the STARGRASP knowledge. In 2009 Cryostat, CCD and STARGRASP technologies were developed for a small camera system for the US Air Force Advanced Electro-Optical System telescope at the Haleakalā Observatory on Maui. A similar project was also completed for the WIYN 0.9m observatory also in 2009 at the Kitt Peak National Observatory in Arizona. This was followed by additional electronics in 2011 and an upgrade in 2015. In 2011 this work also led to developing electronics based on STARGRASP for an infrared camera for Hawai‘i-based Oceanit to detect geo satellites for space surveillance and defense.

Subsequent second generation STARGRASP projects for NASA in 2013 and for the Association of Universities for Research in Astronomy in 2016 also benefited from spillovers from the first generation STARGRASP projects. The original research projects generated spillovers that led to at least $3.2 million of additional projects. Knowledge spillovers from the original and subsequent projects could be expected to continue supporting future projects.

ADAPTIVE OPTICS HOKUPA'A

In 1996 the IfA developed and installed a 36 element adaptive optics wavefront curvature correction system for the Canada France Hawai‘i Telescope (CFHT). The project was called ‘Hokupa‘a’, meaning ‘immovable star’ in Hawaiian. Two venture capital funded projects followed, using knowledge spillovers from this technology for new applications: Zyoptics, and AOptix Technologies. Zyoptics Inc, which was started by two former IfA instrumentalists and based in Campbell, California, operated from 1999 to 2000. AOptix also operated in Campbell California from 2000 to 2001 developing adaptive optical communications technologies.

CONCLUSION

Using survey data collected from astronomy related entities throughout Hawai‘i together with DBEDT's 2017 Inter-County Input-Output Table we calculated the economic impacts generated by the astronomy sector's expenditures in the state. In 2019, the $110.02 million in local astronomy spending resulted in $220.95 million in output of goods and services, $68.05 million in labor income, $10.10 million in state taxes, and 1,313 jobs statewide. The $220 million in output was equivalent to nearly 80% of the total farming output statewide, which suggests that astronomy continues to be a sizable and stabilizing source of economic activity in Hawai‘i. It should be noted, however, that the direct, indirect, and induced economic impacts included in these estimates do not entirely account for the knowledge, expertise, and technology benefits that the astronomy sector generates for the wider economy. Based on discussions with local experts in the astronomy sector, it is clear that these additional benefits are substantial, particularly knowledge spillovers that support future research and local technical manufacturing.

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APPENDIX: EXPENDITURE SURVEY

Organization name: ________________________________
Name of contact: __________________________________
Phone: ____
Email: ____

Category	Description and examples*	Total calendar year 2019 expenditures (to the nearest 1,000$)	% of total calendar year 2019 expenditures by county**			
			Honolulu	Hawai'i	Maui	Kaua'i
Salaries and wages	Salaries and wages paid to employees, including other taxable payments such as high altitude allowances, merit awards, etc. Do not include fringe.					
Employee benefits	Fringe benefit payments, expenditures for business and employee insurance coverage, employee benefit programs and services. Do not include FICA.					
Retirement contributions	State of Hawai'i Employees' Retirement System (ERS), TIAA-CREF, etc.					
FICA taxes	Federal Insurance Contributions Act					
Rent	Expenditures for rental of facilities, equipment, vessels, cars, etc.					
Equipment	Expenditures for capital purchases - durable goods, equipment, motor vehicles, furniture, construction materials, metals and minerals (except petroleum), laboratory equipment, scientific instruments, etc.; include raw and intermediate materials and supplies used in production of astronomy related equipment					

Supplies	Office supplies, consumables, minor equipment					
Information	Internet, telecommunications, media services					
Utilities	Electricity, gas, water					
Travel	Expenditures for airfare, lodging, meals & incidentals paid on behalf of employees and others such as event participants, invited guests, etc. Please provide total and breakdown of lodging costs and airfare/ground transportation if available OR provide a best estimate for lodging and airfare %.					
	Lodging (amount or %)					
	Airfare/gr transportation (amount or %)					
Professional services	Expenditures for services such as accounting and payroll; computer support; consulting; research; advertising, engineering, architectural					
Financial & insurance services	Investment management services, expenditures for interest on loans or leasing arrangements					
Business services	Waste management and remediation services; security and surveillance services, cleaning					
Transportation	Expenditures to transport materials and equipment via air, water, truck, rail, etc.; include warehousing and storage en route					
Repair & Maintenance	Equipment and machinery repairs and maintenance; Observatory and other building repair and maintenance; Safety inspections					

Construction	Heavy & civil engineering construction; Construction costs incurred for observatory and other buildings					
Taxes	Payroll taxes other than FICA, real property taxes, income taxes, import taxes					
Other***	(Please describe)					
Please report the number of FTE employees in each category, by county						
FTE Category	Examples	Honolulu	Hawai'i	Maui	Kaua'i	
Scientific research	Researcher, faculty, graduate student, post doc, etc.					
Technical support	Engineer, technician, other trades, etc.					
Administrative support	Manager, clerical, financial, etc.					

* For Mauna Kea observatories, do not include Mauna Kea Observatories Support Services payments. These will be handled separately.

** If the actual dollar amount spent in each county is not available, please estimate the percentage.

*** "Other" expenditure category is a catch-all to account for all institution expenditures in calendar year 2019. Use this category for expenditures that were not captured in the above specified categories and provide as best as possible a brief description of the expenditure. Use this category if you are not sure whether a particular expenditure belongs to any other above specified categories.

Please note that you can make more than one entry in this category. For each entry, please provide a description/explanation along with each expenditure amount e.g., tuition payments for employees - $XXX", x%; publication costs - $YY, y%. We encourage you to make multiple entries in situations where there is more than one expenditure type that cannot be included in one of the specified categories. If you need more space for the category "Other" please attach another page.

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