

Astronomy Education Journal, 2023, Vol. 03, No. 1

doi: 10.32374/AEJ.2023.3.1.052resana ISSN: 2004-2981 • Published in Sweden

RESOURCE ANALYSIS

Video as a Vehicle for Astronomy Education and Outreach

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Abstract

Video is an excellent vehicle for astronomy education and outreach. Usage patterns and user demographics are presented for short videos covering a variety of astronomy topics, delivered to public audiences from three websites, three YouTube channels, and three massive open online classes, or MOOCs. The data spans over a decade in some cases. The modality of the content ranges from short lecture presentations of sub-topics in astronomy to longer scripted pieces created by students to Q&A sessions held by the MOOC instructor with live audiences of 100-200. In the aggregate, the videos have attracted 1.2 million views, and those viewers have watched 77,300 hours of astronomy content. Most of the viewers are not based in the United States. Viewership rose dramatically at the outset of the COVID-19 pandemic and has not yet returned to pre-pandemic levels. The videos watched by lifelong learners taking a MOOC show a decline in usage as they progress through the online course. But on these YouTube channels, when viewers can choose among the topics, the most popular are cosmology and exoplanets. Suggestions are made for the effective ways to create and disseminate astronomy videos.

Keywords: Video; science communication; education; outreach; YouTube

1 Introduction

1.1 The Rise of Educational Video

Video content on the Internet has grown dramatically over the past decade, transforming the way people learn and experience information. As anticipated by Cisco, Internet video traffic grew at a rate of 34% per year from 2017 to 2022, to become over 80% of all traffic (Cisco, 2018). Much of the growth has come from streaming services that deliver TV shows and movies to the home or to mobile devices (Linker, 2022). The giant of video content is YouTube, operated since 2006 by Google. YouTube is the second most popular website in the world, with 1.7 billion unique monthly visitors. In the United States, 62% of all Internet

users go to YouTube daily, spending an average of 19 minutes there (McLachlan, 2022). In the YouTube ecosystem, viewing is skewed such that 85% of all views go to only 3% of the channels (Bärtl, 2018).

Most video on the Internet is purely for entertainment, but video has obvious attraction for science education and outreach. The medium enables storytelling and conveys a vivid sense of place, attributes that are known to increase student engagement and learning (Nelson, 2011; Brame, 2016). A pioneer of high-quality, short (under 20 minutes) videos for public audiences is the TED organization (Technology, Entertainment, Design), a non-profit begun in 1984 that has published over 3900 videos online, many on science topics (Sugimoto and Thelwall, 2013). YouTube is the place where free-choice learners typically go to find science videos (Rosenthal, 2018). Short format

videos can be created without any professional production capabilities, and user-generated content can be just as popular as professional content (Welbourne and Grant, 2016; Pattier, 2021). The most popular half dozen channels on YouTube as of May 4, 2022, in the categories "education" and "science and technology" are Mark Rober with 21.5 million subscribers, TED with 21.0 million subscribers, Kurzgesagt with 19.2 million subscribers, a TED spin-off called TED-Ed with 16.6 million subscribers, Crash Course with 13.4 million subscribers, Veritasium with 11.7 million subscribers, and SciShow with 7.1 million subscribers (Reemer, 2022).

YouTube is not only a video sharing platform, but a business, and as such operates in a way to drive the most traffic possible to their site and retain viewers. They have created algorithms designed specifically to keep people watching by suggesting certain types of content and videos based on a viewer's watch habits, and these algorithms have gone through many iterations over the years. This means that educational YouTube channels cannot solely focus on creating interesting, worthwhile content, but they also must cater to an algorithm whose details are undisclosed (Airoldi et al., 2016). Because the specific workings of this algorithm are kept secret by YouTube, we are not able to definitively point to any changes in our data as caused by alterations to the algorithm, but it is a possibility.

1.2 Videos for Astronomy Education and Outreach

Astronomy has singular advantages for outreach using video, thanks to the visual beauty of the universe and the dynamic nature of many astronomical phenomena. National media producers like PBS/NOVA and National Geographic have been creating videos for television broadcast for years. Shorter videos can be found on YouTube, including many on the channels listed in the previous section. An anonymous search on Google for astronomy videos on YouTube as of May 4, 2022, returned 3.8 million results, with about 100,000 additions each month. The most popular videos are in the SciShow Space channel, with over 200 million views. Videos in the Kurzgesagt series have 180 million views and Astronomy Crash Course videos have 105 million views. A cosmic size comparison video by Harry Evett has 133 million views and "Solar System 101" from National Geographic has 23 million views. There are many other videos with over a million views that are single astronomy lectures at public events or single episodes from television shows for a national audience.

This paper reports on videos that are not near the Olympian heights of viewership of the most popular YouTube channels. However, they have more than a million views and they carved out a niche in astronomy as videos that students and lifelong learners learn from and enjoy. Since 2011, our group has operated a website for astronomy education and outreach called "Teach Astronomy" (Impey et al., 2016a; Impey and Danehy, 2017). Videos were created and posted on a YouTube channel with that same name. A large set of short clips from the YouTube channel have also been hosted by Apple, originally under their iTunes U umbrella and more recently as podcasts. Since 2013, we have been offering massive open online classes, or MOOCs, to lifelong learners around the world. The providers for these courses are Udemy and Coursera, but the lecture videos are also hosted on the "Teach Astronomy" and "Astronomy State of the Art" YouTube channels (Impey et al., 2015, 2016b). Another type of video content can be found on the "Active Galactic" YouTube channel. Since 2015, short videos on varied astronomical topics have been planned and executed by teams of undergraduate students (Impey et al., 2018). Data for these videos is reported through the end of May 2022. The remainder of this paper

presents the usage patterns and user demographics of these digital assets, along with suggestions on how to create and curate astronomy videos for education and outreach.

2 Videos on Teach Astronomy

2.1 Short Videos on all Topics

The largest dataset discussed in this paper is 1128 short videos, each 1-2 minutes long, grouped into 29 playlists, covering all topics in astronomy. They were filmed in early 2011 using a green screen to allow for varied backgrounds with the instructor appearing as a "talking head". Each clip covers one sub-topic in astronomy, with content loosely based on the first author's introductory astronomy textbook called "The Universe Revealed" (Impey and Hartmann, 2000). They have periodically been updated and augmented over the years. Short videos like these are brief overviews of a topic, designed for people with little or no background in astronomy. Their target audience is a student in an introductory astronomy class or a lifelong learner with a casual interest in the subject. Amateur astronomers and serious students of astronomy would typically want more information and greater depth.

The entire collection has received 618,600 views and the weekly history is shown in Figure 1a. Among these clips, 5 have 10,000-15,000 views, 14 have 5,000-10,000 views, 49 have 2,000-5,000 views, and the bulk of them have under 1000. The watch time, shown in Figure 1b, tracks with the views. Total watch time for all the clips is 7,700 hours. The number of views per week increased to a broad peak from 2013 to 2016 followed by a continuing decline. The eight "spikes" that can be seen in the data are all between September and November but are not all at the same date. Notably, there was no growth in viewers during the COVID-19 pandemic. In fact, viewership declined through the peak of the pandemic. This is in contrast the MOOC lecture videos and live Q&A sessions described later in the paper, which both showed pandemic "bumps". It is speculated that the pandemic drew more people to the full-course video content of a MOOC than to the bite-sized topical content of the short clips. Viewers watched an average of 70% of each video, as shown in Figure 1c.

The percentage viewed increased from 65% in 2012 to 75% more recently. We note that YouTube only had provided the watch time and percentage viewed since 2012. The weekly data show clear minima in views for a week or two at the end of each year, and for several months each summer. This is more clearly displayed in Figure 2a, which bins the data by the number of weeks into the year and combines all years. Watch time shows the same pattern, see Figure 2b. The peak viewing was from September through November. This usage pattern is typical of students who access science content during the school year or the college year but not over the vacations.

The following metrics apply to the entire "Teach Astronomy" YouTube channel, but 90% of the views are from the short clips described in this section. The subscriber count for the YouTube channel shows interesting, and counter-intuitive, features. Number of subscribers added monthly is shown in Figure 3a. The number was initially low but rose at the end of 2015, when MOOC videos were added to the channel, then surged by a large factor as the pandemic hit in March 2020, only to decline again as the pandemic abated. Strangely, the added subscribers did not heavily engage in the content, as views and video watch time both declined through the pandemic. Cumulative subscribers are shown in Figure 3b. Visitors to the videos came from 94 countries. Half of the traffic came from the United States



Figure 1. Views (1a, top), watch time (1b, middle), and average percentage of each video viewed (1c, bottom) for 1128 short videos on astronomy sub-topics from the Teach Astronomy YouTube channel.

(49.5%), and the next four countries in terms of viewers were the United Kingdom (6.5%), India (5.1%), Canada (4.6%), and the Philippines (2.7%). No other country accounted for more than about 1% of the viewers. Viewers from the U.K., in particular, mostly disappeared as the pandemic started. In terms of device types, about 60% of viewers access the content via a computer, but the proportion using smartphones has grown from a sixth of the number of computer users to half recently.

Looking at traffic sources, as displayed in Figure 4, 44% of all traffic to the channel is a result of the YouTube search function. The second highest traffic source at 24% is contributed by external sources. Just over half (51%) of this external traffic is



Figure 2. Views (2a, top) and watch time (2b, bottom) for short video clips from the Teach Astronomy YouTube channel, summed over weeks into the year from 2011 to 2022.

credited to Google Search, while the remainder is spread among different websites that have linked to or embedded the videos. These numbers show that the Teach Astronomy channel's content is typically found through a search for specific topics and not by people returning to watch multiple videos of the same type. This allows us to gain a clearer idea of what topics viewers are seeking out most often.

The topics of the twenty most popular videos show no obvious pattern, ranging from history (solar and lunar calendars) to positional astronomy (perihelion and aphelion) to stars (protonproton chain) to basic physics (Wein's law). However, three of the top four are about compact stellar objects (Chandrasekhar limit, Schwarzschild radius, and degenerate matter), reflecting the well-known public fascination with exotic end states of stars.

Yet the video on Black Holes is in the bottom quarter of popularity and other major topics like Life in the Universe and Extrasolar Planets are near the bottom of the list. The short videos are organized in 29 playlists that mirror the usual flow of topics in introductory astronomy textbooks. A broader brush sense of the relative popularity of topics is given by the total views by playlist, shown by the blue bars in Figure 5. The most popular playlists are the first three in a typical textbook sequence, on the scientific method, ancient astronomy, and basic concepts in physics. A second, independent repository of these videos was hosted by Apple. They were initially uploaded to iTunes U, which Apple launched in 2007 to host lectures from top U.S. colleges (McKinney et al., 2009). Collections in iTunes U started getting views in 2011, they were moved over to Apple Podcasts in 2017, and in 2021 iTunes U was discontinued. As hosted by Apple, the entire collection received 51,900 streams and downloads combined, and it attracted 3,107 subscribers. The breakdown by playlist is shown by the orange bars in Figure 5. The most popular three topics are ancient astronomy, the big bang, and geology and physics.

2.2 Coursera MOOC Videos

A massive open online class (MOOC) on astronomy called "Astronomy: Exploring Space and Time" was launched on Coursera in 2014 (Impey, 2022). As of May 4, 2022, it had 192,000 students enrolled and an average rating of 4.8 out of 5 stars based on 3,200 reviews. Lecture videos were filmed using a green screen, allowing for varied backgrounds of Hubble Space Telescope images. Images, animations, simulations, and movie clips were interspersed with the lecturer's talking head. The videos were uploaded to the "Teach Astronomy" YouTube channel in 2015. They consist of 11 playlists, one for each module of the course, or 142 videos in total, ranging from under 5 minutes



Figure 3. Number of subscribers added per month (3a, top) and cumulative subscribers (3b, bottom) for the Teach Astronomy YouTube channel, where 90% of the traffic is for the short video clips.



Figure 4. Sources of the Teach Astronomy channel's traffic, where 90% of all traffic goes to the short video clips.



Figure 5. Number of views for the 29 playlists that organize the 1129 short video clips on astronomy sub-topics. Orange shows the views on YouTube and blue shows the views on iTunes U.

to over 15 minutes long. The lectures were designed for freechoice adult learners in a MOOC but their presence on YouTube allows anyone to browse the channel or find individual videos from a Google keyword search. The production values are on a par with other prominent astronomy videos on the web.

The Coursera course videos have a total of 71,460 views and the weekly history is shown in Figure 6a. Among the videos, one has over 15,000 views, another has over 5,000 views, 12 have 1,000-3,000 views, and most of the rest have a few hundred views.

The watch time per week, in Figure 6b, tracks the number of views, and the total across all videos is 4,820 hours. The number of views per week increased steadily, with a peak in 2017 to 2018, then a slight decline, with no sign of an increase during the pandemic. This contrasts with history of the MOOC for which these videos were created, which witnessed a dramatic enrolment surge when the pandemic started (Impey and Formanek, 2021). On average, viewers watched 40% of each video, a percentage that has increased over six years, from 35% to 45%, as shown in Figure 6c. Like the short videos, the longer MOOC videos show a pattern in the number of viewers through the year, with a broad dip in the summer and a short dip at the end of the year. This is readily seen in Figure 7a, which sums the data by weeks into the year over all years. Watch time shows the same pattern, as seen in Figure 7b. Unlike the short videos, the course videos show sharp peaks in viewership in January and September. These are the first months of the semesters in an academic calendar, maybe indicating that people who start to follow the course then do not persist.

By far the most views, over 15,000, or almost three times the views of the next most popular video, are for the cosmology lecture called "The Multiverse". This video also generated by far the most subscribers (216), likes (434), and comments (40).

The total numbers for all videos were 520 subscribers, 1365 likes, and 159 comments. Six of the videos with more than 1,000 views, or over 40%, are the lectures on the history of astronomy. Otherwise, there is no obvious pattern of popularity through the 142 videos of the MOOC. People seeing videos on YouTube can select topics according to their interests. By contrast, those taking a MOOC have to pass through the subject linearly, with substantial attrition since only a small fraction of the people who start go on to complete the class (Impey et al., 2016a). As a result, far fewer will watch the cosmology videos than the history videos at the beginning of the class. The two most popular videos on YouTube (extremophiles and multiverse) were watched by a fraction of the MOOC learners who started the online course.

There was a significant spike in the impressions during the week of April 28, 2019. Impressions count the number of times the video thumbnails were shown to viewers. Recall that YouTube has proprietary and secret algorithms that drive how thumbnails are shown to website visitors. While normally 900-4,000 per week, this specific week saw 32,844 impressions. This was most probably due to the release of an updated version of the "Astronomy: Exploring Time and Space" course. An important, related metric is the impression click-through rate which measures how often viewers watched a video after clicking on the thumbnail. A view means that the video has been at least started and watch time measures how long on average the video was played.

2.3 Book Reading Videos

A last group of videos, and the only content less than two years old on the "Teach Astronomy" channel, is a set of 23 book readings done by one of us (VP), based on two trade books written by the first author, "Dreams of Other Worlds" (with co-author Holly Henry) and "Einstein's Monsters" (Impey, 2016, 2019). The most watched chapter has 250 views and the majority have between 50 and 100 views. Since the last of this video content was syndicated live in July 2021, the number of weekly views has declined. The total number of views is 2,000 and a total of 138 hours have been watched. Viewers watched an average of less than 10% of each video. Without a concerted effort to publicize these readings, they are unlikely to attract the same audience that is easily attracted for a full astronomy course.

3 Videos on Astronomy State of the Art

3.1 Udemy MOOC Videos

Our first massive open online class on astronomy, called "Astronomy - State of the Art," was launched on Udemy in 2013 (Impey, 2022). As of May 4, 2022, it had 112,000 students enrolled and an average rating of 4.7 out of 5 stars based on 4,500 reviews.



Figure 6. Views (6a, top), watch time (6b, middle), and average percentage of each video viewed (6c, bottom) for the Coursera MOOC videos from the Teach Astronomy YouTube channel.

Lecture videos were filmed in similar fashion to the Coursera course. The videos were uploaded to the "Astronomy: State of the Art" YouTube channel in 2013, so there is more data for them than for the Coursera videos (two additional recent MOOCs on Coursera, called "Astrobiology: Exploring Other Worlds" and "Knowing the Universe: The History and Philosophy of Astronomy", were either published on YouTube after this paper's data was collected or have not been made public yet). They consist of 7 playlists, one for each section of the course, or 49 videos in total, ranging from under 8 minutes to over 22 minutes long. The Udemy MOOC is similar coverage and structure to the Coursera MOOC discussed previously, and is aimed at a similar audience.



Figure 7. Views (7a, top) and watch time (7b, bottom) for the Coursera MOOC videos from the Teach Astronomy YouTube channel, summed over weeks into the year from 2013 to 2022.

The Udemy course videos have a total of 45,400 views and the weekly history is shown in Figure 8a. The watch time per week, in Figure 8b, roughly tracks the number of views, and the total across all videos is 2,230 hours. The number of views per week increased, with a peak in 2014 to 2018, then a slight decline, followed by a sharp rise near the beginning of the pandemic. On average, viewers watched 45% of each video, a percentage that did not change over nine years, see Figure 8c. The largest number of views, over 11,000, are for the promotional video for the course. The next three most popular videos, with 4,000 to 8,000 views, are about adaptive optics, the Jovian planets, and active galaxies. Three other videos have around 1,000 views and the remainder have a few hundred each, with no obvious pattern for the topics that are more popular. Overall, the videos generated 500 likes and 209 subscribers to the YouTube channel.

3.2 Live Q&A Session Videos

Soon after the Udemy MOOC launched in 2013, we started doing live question and answer (Q&A) sessions with the instructor (CI) and posting them soon after on the "Astronomy: State of the Art" YouTube channel. The frequency of the sessions is roughly every two weeks, increasing to weekly during the pandemic, with occasional gaps of 3-4 weeks due to travel and holidays. In October 2020, we started interleaving Twitch live sessions with the traditional YouTube Live sessions. Questions are fielded in two ways: from participants on the live stream or by email ahead of time. The number of live participants averages around 100, with peak participation slightly over 200. Each session lasts about an hour and 30-35 questions are typically asked during that time. As of May 4, 2022, there have been 181 live sessions. The questions are wide-ranging and cover all areas of astronomy, with an emphasis on recent discoveries or astronomy that has been in the news. Some questions relate to observing with small telescopes and preparing for a career in astronomy.

All the sessions have more than 200 views, and most of them have between 500 and 1,000. During the pandemic, attendance at the live sessions jumped, even as their frequency increased. Of the 38 Q&A live session videos with over 2,000 views, all but two are from the last two years. The total number of views is 226,300 and 53,450 hours of these videos have been watched. The weekly history of views is in Figure 9a, which tracks the watch time per week, shown in Figure 9b.

On average, viewers watched about 30% of each video, a duration of 20 minutes, see Figure 9c. The live sessions have been gaining more traction over time; the percentage viewed has increased from 10% to 50% since they have been offered. The 181 live sessions have generated a total of 9,500 likes and 18,940 comments, affirming a high level of viewer engagement. This



Figure 8. Views (8a, top), watch time (8b, middle), and average percentage of each video viewed (8c, bottom) for the Udemy MOOC videos from the Astronomy State of the Art YouTube channel.

popularity is surprising, since topics covered in any live session vary from question to question, so people viewing the videos cannot predict when a particular topic will come up. They presumably maintain a keen and broad interest in astronomy.

The following metrics apply to the entire "Astronomy State of the Art" YouTube channel, where 20% of the views come from the

Udemy course videos and 80% come from the live Q&A session videos.

The statistics of weekly viewers show no obvious trends within a year, suggesting informal learners as opposed to students taking an astronomy class. Views, hours watched, and number of subscribers all rose sharply as COVID-19 surged around the



Figure 9. Views (9a, top), watch time (9b, middle), and average percentage of each video viewed (9c, bottom) for 181 live question and answer (Q&A) sessions from the Astronomy State of the Art YouTube channel.

world. In particular, after taking seven years to reach 4,500 subscribers, it only took seven months during the pandemic to increase more than double, as seen in Figure 10a. The cumulative subscriber total can be seen in Figure 10b. Over two years into the pandemic, they remain above pre-pandemic levels.

Visitors to the videos came from 72 different countries. A

quarter of the traffic came from the United States (24.7%), so the audience for videos and live sessions related to a MOOC is more international than the audience for the short astronomy clips described previously. The next three countries in terms of viewership were India (5.7%), the United Kingdom (3.7%), and Canada (1.6%), with no other country accounting for more than



Figure 10. Number of subscribers added per month (10a, top) and cumulative subscribers (10b, bottom) for the Astronomy State of the Art YouTube channel, where 80% of the traffic is for the live Q&A sessions.

1% of the viewers. In terms of device types, 52% of viewers have accessed the content via a computer, but the proportion using smartphones has grown from a tenth of the number of computer users to exceed the number of computer users in the past year.

Impressions across the channel saw an immediate bump at the start of the COVID-19 pandemic lockdown in 2020. While regular impressions for the channel fluctuated in the thousands before this, between April 2020 and May 2021, impressions only dipped below 10,000 four times. This indicates that our videos were being suggested to a much larger audience during this period, likely due to influence from the YouTube algorithm responding to an influx of viewers while people were quarantining at home and consuming more content. While these numbers have not stayed as consistently high as they were, average impressions per week between June 2021 and April 2022 were 13,440, suggesting a permanent increase in the frequency YouTube is suggesting this content.

4 Videos on Active Galactic

4.1 Student-Created Videos

The most innovative project described in this paper is led and organized by undergraduate students in the first author's edu-

cation research group at the University of Arizona. The "Active Galactic" YouTube channel hosts 125 short videos, as of May 4, 2022, dating back six years. Subjects range from what astronomers do to tours of major observatories to a series of "Five Facts" videos to a musical version of the Hertzsprung-Russell diagram (Impey et al., 2018). Students work in teams to pitch ideas, write scripts, film and edit the videos, add soundtracks, animations and visual effects, and distribute the videos online. All the videos have a strong student voice and benefit from their experience with social media. The total number of views is 300,600. Six videos have over 15,000 views, 11 have between 3,000 and 15,000, and 29 have between 1,000 and 3,000. The total watch time is just over 10,000 hours and on average viewers watch 50% of each video. Overall, they generated 18,700 likes and 1,800 comments on YouTube.

The only commonality to the most popular videos is their tendency to have one or more engaging student narrators onscreen. The six with the most views are an explanation of the H-R diagram, a tour of a VLBA radio dish, a humorous description of what astronomers do, a timelapse of a 2018 lunar eclipse, an explainer on Aristarchus, and a tour of the Large Binocular Telescope in Southern Arizona. The "singing" H-R diagram drew seven times more likes and fifteen times more comments than any other video, while the VLBA video attracted ten times more subscribers than any other video. This is likely due to our collaboration with a prominent, fellow science YouTuber. A video about making the world's largest telescope, The Giant Magellan Telescope, was featured on Tom Scott's YouTube channel, which has five million subscribers (YouTube 2022). This single video has over 380,000 views, more than all the other Active Galactic videos combined. When this video was posted by Tom Scott in early 2018, the Active Galactic channel immediately gained 5,500 subscribers and it saw an increase in views that has persisted ever since.

The weekly history of views is shown in Figure 11a. There was steady growth from 2015 through 2017, with no evidence of seasonal variations. Then there is a spike due to traffic from Tom Scott's channel, with some residual referral traffic for a few months, followed by a steady decline in viewers. This probably reflects the fact that relatively few videos have been released in the channel in the past few years. Hours watched tracks views fairly closely, see Figure 11b, and the percentage of each video watched have fluctuated between 40% and 50% over the last six years, as shown in Figure 11c. The subscriber boost from Tom Scott was also dramatic, jumping from 415 to 5,000 in a month at the end of 2017. Since then, the channel has gained another two thousand subscribers, as shown in Figure 12a. The cumulative subscriber count is in Figure 12b.

The channel has gradually seen an increase in international traffic since the first video was posted in November 2015. Visitors to the videos came from 68 countries. The United States accounted for 42% of the traffic. The next highest proportions are from India (4.9%) and the United Kingdom (4.3%). The next six countries are the Philippines, Germany, Canada, Australia, the Netherlands, and Sweden, all with under 2%. As with the other videos discussed in this paper, the way people choose to view them has changed over time. Relative to access by desktop or laptop computer, access by a tablet device increased slightly from 20% to 25% from 2016 to 2019, but intriguingly, declined over the past two years to 15%. Meanwhile, as with our other YouTube channels, mobile phones have become the device of choice, increasing from a third of the rate of computer access in 2016 and to exceed the rate of computer access in 2021 and 2022.

Similar to Teach Astronomy, the Active Galactic channel's main source of traffic is through YouTube Search. This supports the idea that a majority of viewers watching shorter educational videos are looking for videos on specific topics rather than watching through a channel's history. Besides the significant jump in traffic from End Screens and Channel Pages that resulted from the collaboration with Tom Scott, the YouTube Search has been the main source of traffic since 2018 and represents 33% of all traffic on the channel.

5 Discussion

The varied astronomy videos discussed in this paper have been viewed 1.2 million times and they have accumulated over 77 thousand hours of viewership. They serve formal education audiences like college students taking an introductory astronomy class and informal audiences such as lifelong learners enrolled in a massive open online class or people simply interested in astronomy. All these videos were created by the authors, assisted by a rotating cast of undergraduate students who helped with scripting, filming, editing, and dissemination. This talent enables videos to be created on a modest budget. The hardware and software used for this project have been discussed elsewhere (Impey et al., 2018).

We have given workshops on how to create engaging videos and use platforms like YouTube to maintain an audience (Wenger and Gay, 2019). However, research on the factors that make for a successful educational video is relatively sparse (Wade and Courtney, 2013; Yoo and Catrambone, 2016; Velho et al., 2020; Pattier, 2021; Shen et al., 2022). YouTube has evolved its algorithm, which over 80% of users say guides their viewing (Smith et al., 2019). For YouTube's early years, videos were rewarded for clicks or views. In 2012, their algorithm started to give increased priority to watch time (Singh, 2022). In 2016, YouTube began using neural nets and machine learning in its recommendation system (Covington et al., 2016). Complex algorithms can introduce subtle but profound biases in the videos that are offered up to YouTube users (Kirdemir et al., 2021). As a result, we cannot elucidate a particular recipe for success based on our experience, however we can summarize patterns we observed and lessons we learned that might be helpful to others planning to create educational videos.

- There is a sizeable audience for bite-sized video information on astronomy. The thousand-plus, 1-2 minute clips had over 600,000 views and were most likely used by students taking an astronomy class. We plan to move further in this direction by filming a video "talking glossary" of astronomy terms and delivering that content and the short clips by verbal request to a smart speaker like those sold by Amazon and Google (Terzopoulos and Satratzemi, 2020).
- Astronomy content has a global audience. Over half the audience for the videos came from outside the United States, spread among 106 countries. For the MOOC videos and videos of the live Q&A sessions, three quarters of the viewers were foreign. The most popular topics are cosmology, compact objects like black holes, exoplanets, and the history of astronomy.
- Somewhat surprisingly, hour-long Q&A sessions on any topic in astronomy were very popular. They continue to attract over 100 people online live, and a typical Q&A session has over 1,000 views, racks up 300 hours of watch time, and attracts 100 comments, all of which indicate a high level of viewer engagement. This is despite the fact that the questions occur in no particular order.
- The effect of the ongoing COVID-19 pandemic on access to science content is seen in the usage patterns described in this paper. While the boost was not as strong as the surge in enrollment in the MOOC itself (Impey and Formanek, 2021), the same videos on YouTube saw a sizeable increase in viewers which has not yet returned to the pre-pandemic level.
- The entrepreneurial energy of undergraduates can be harnessed to create short astronomy videos for a wide audience. In this case two dozen students created 125 videos over a 6-year period, garnering 300,000 views. The process of scripting, filming, and editing videos can powerfully boost student learning, as well provide excellent content for outreach purposes (Greene, 2014; Wang and Shao, 2016). Many astronomy educators could try this type of experiment.
- The average viewer watched about half of each video. Intriguingly, the percentage did not depend strongly on the length of the video. Over the course of the project, access by our audiences to YouTube videos by mobile phones increased to exceed access by laptop or desktop computers in the past few years.
- Shorter educational videos are most often found by viewers through search functions like YouTube Search or Google Search, suggesting that the topics that receive the most



Figure 11. Views (11a, top), watch time (11b, middle), and average percentage of each video viewed (11c, bottom) for 125 short videos created by students from the Active Galactic YouTube channel.

views are topics more sought after by viewers. This information can be used to choose future video topics and tailor projects to the most desired subjects.

YouTube is not the only way to disseminate videos, but it is a leviathan of the Internet and the easiest and the most creator-

friendly vehicle for publishing video content. Over the decade of this project, YouTube has grown from a billion annual users to 2.5 billion, 500 hours of content are now uploaded every minute, and the high-water marks are currently 200 million for subscribers to a single channel and 10 billion for views of a single video (Iqbal, 2022). While the majority of YouTube users look



Figure 12. Number of subscribers added per month (12a, top) and cumulative subscribers (12b, bottom) for the 125 short videos created by student from the Active Galactic YouTube channel.

to the platform to help them figure out things they've never done before, educational content is a small fraction of the overall content (Smith et al., 2019). Moreover, popularity as measured by views or likes is not a direct indicator of quality, and the efficacy of videos for science communication has not yet been established (Kohler and Dietrich, 2021).

For anyone starting a project to create astronomy videos, getting traction is a substantial challenge since the lion's share of viewers go to a very small fraction of channels (Bärtl, 2018). Our experience is that modest resources are sufficient to create appealing and informative videos that serve the dual purposes of education and outreach. Guidance is available when it comes to best practices (Johanes and Lagerstrom, 2016). We would encourage any astronomy instructor to set realistic expectations and start experimenting with video as a learning tool.

6 Acknowledgements

We acknowledge support from the Department of Astronomy to help with website hosting and the University of Arizona for assistance filming MOOC videos. Much of this work was done during the five years Chris Impey was partially supported by an HHMI Professor grant from the Howard Hughes Medical Institute. This project has greatly benefited from the hard work, expertise, and enthusiasm of over three dozen undergraduates who have worked on various aspects of the videos. In particular, we would like to acknowledge the substantial contributions of Kevin Hardegree-Ullman, Carmen Austin, Jenny Calahan, and Michael Hardegree-Ullman.

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