

ArgusSpec: rapid, autonomous spectroscopic follow-up of bright transients

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ABSTRACT

ArgusSpec will be a fast-response, low-resolution spectroscopic follow-up system. Built almost entirely from off-the-shelf components, including a medium-aperture (16-in.) Ritchey-Chrétien telescope, a very-low-noise CMOS detector, a low-resolution ($R \sim 100$) spectrograph, and a fast-slew (50 deg/s) mount, ArgusSpec will begin observations of bright transient events ($m_V \leq 13$) within tens of seconds of detection. ArgusSpec will use all-sky transient alerts from the Evryscope, the Argus Pathfinder, and the planned full Argus Array; the latter two systems giving the fastest alerts for optical transients to date. Until now, the high-cadence sky has been largely inaccessible for spectroscopy. For example, large flares from active stars have dramatic impacts on orbiting exoplanets, but are difficult targets for spectroscopic follow-up due to their short-timescale evolution. Planets in the active stars' habitable zones will be impacted by flares and superflares (energies $\geq 10^{33}$ erg), and associated high-energy particle emissions, which could strip the planet of its atmosphere and impart massive amounts of ultraviolet flux; this could be devastating to any life on the planet's surface. There has not been a systematic spectroscopic survey of energetic flaring events across a wide range of stellar masses; almost all large flares observed spectroscopically have been from a small sample of active mid-M stars through staring campaigns. For the first time, ArgusSpec will build a library of superflare spectra from across the night sky, allowing for statistical constraints to be placed on their blackbody evolution and morphology. Here we present the design, project status, and science drivers of ArgusSpec.

Keywords: ArgusSpec, transients, flares, low-resolution spectroscopy, rapid follow-up

1. INTRODUCTION

The Evryscopes are a pair of northern and southern telescope arrays consisting of 24 6.1-cm aperture telescopes on shared mounts.^{1,2} By optimizing for cadence and field-of-view, instead of survey depth and sky sampling, they have shown the short-timescale transient sky to be full of interesting astronomical phenomena. For example, by monitoring large numbers of active stars at high cadence, the Evryscopes have made new discoveries and placed constraints on flare and superflare activity that could impact potentially-habitable exoplanets. Observations from Evryscope-South have been used to discover the first superflare from Proxima Centauri,³ characterize hundreds of other flares and superflares by placing constraints on flare frequencies, energies, and blackbody temperatures,⁴⁻⁶ and place constraints on TRAPPIST-1 superflare occurrence and planetary habitability.⁷

In recent years, affordable low-noise CMOS sensors and medium-aperture telescopes have made the next generation of the Evryscope, called the Argus Optical Array, reasonable to build at the mid-scale funding level. The Argus Optical Array will be a 900-telescope array, consisting of mass-produced, eight-inch telescopes and high-speed sensors, that will monitor the entire visible night sky at high cadence. At standard operating cadence, 30 second exposures, Argus will monitor sources down to $m_{g'} = 19.1$. Argus will have a secondary high-speed mode which will increase the observing cadence to 1s with a limiting magnitude of $g' = 16.1$.⁸

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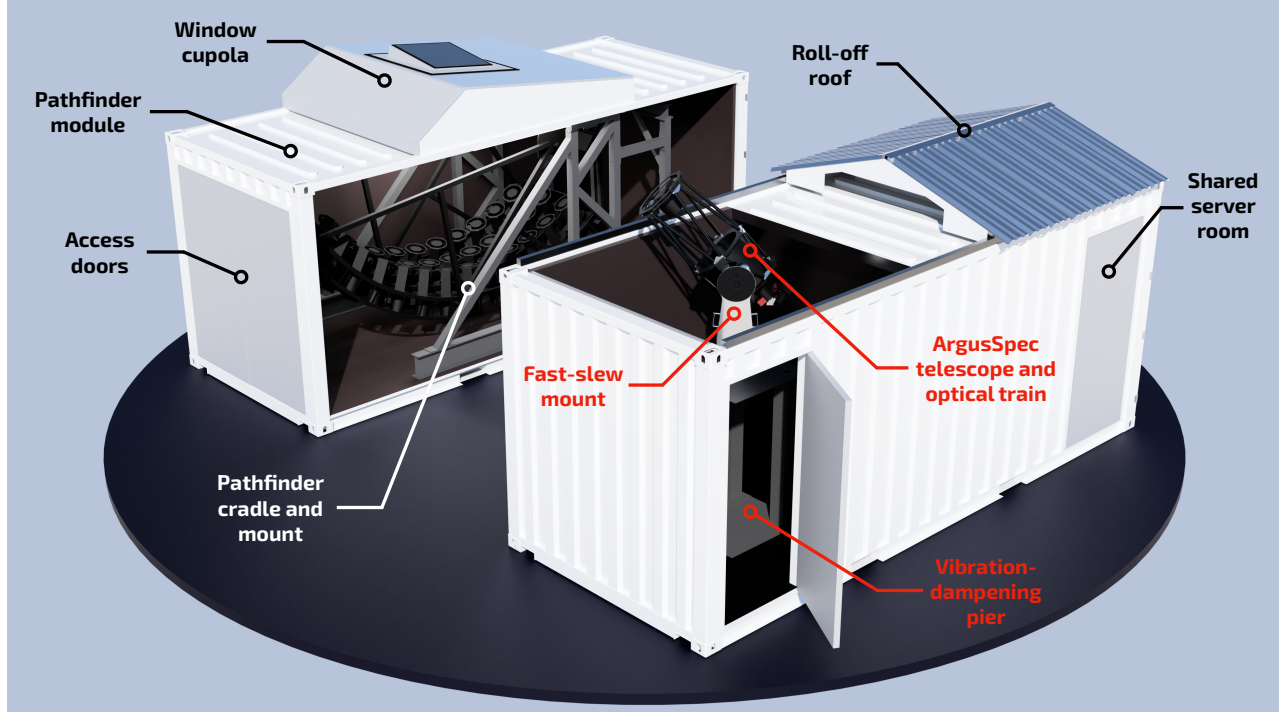


Figure 1. ArgusSpec and Argus Pathfinder combined system concept rendering. Key ArgusSpec components are labeled in red. Both telescopes are placed in portable, weather-sealed containers. ArgusSpec is mounted on a steel, vibration-dampening pier and when not observing is protected under a roll-off roof. The two systems will be deployed alongside one another at a dark-sky site located at PARI in western North Carolina.

Argus is currently in the prototyping phase, with the Argus Pathfinder coming online later this year. Pathfinder will be an array of 38 telescopes, mounted in a hemispherical cradle and designed such that all of the telescopes look through a single window in a weather-sealed and climate-controlled container.⁹ Pathfinder will monitor a stripe of the sky from declination -20° to 72° , building up 15 minutes of observations for the entire visible sky over the course of an observing night. Similar to the Evryscopes,¹⁰ Argus and Pathfinder will produce real-time transient alert streams, which provide rapid information about time-sensitive detections across the night sky. The Argus Pathfinder is currently funded by an NSF MSIP grant and a grant from Schmidt Futures.

Full characterization for many of the transient detections requires not only having high-cadence photometry, but also spectroscopic data. ArgusSpec will be a fully autonomous, rapid-slew spectroscopic follow-up system designed specifically to characterize bright transient detections from the Evryscopes, Pathfinder, and the planned Argus Array. ArgusSpec will receive transient detections from our all-sky telescopes, rapidly slew to interesting targets and begin observations of the event within tens of seconds of detection. ArgusSpec takes advantage of new low-noise CMOS detectors, and by binning to gain signal-to-noise (SNR), will operate at low-resolution and high-cadence. ArgusSpec utilizes a direct-drive mount capable of moving 50 deg/s , allowing it to slew to almost any part of the sky within seconds. ArgusSpec is being built in a portable weather-proof container alongside the Argus Pathfinder (Fig. 1). After the development phase, both systems will be deployed to a dark-sky site at the Pisgah Astronomical Research Institute (PARI). In this paper, we discuss ArgusSpec’s primary science mission (Section 2), instrument hardware (Section 3.1), access to real-time transient alerts (Section 3.2), and give a project status update (Section 3.3). We conclude with a summary of the ArgusSpec project (Section 4).

2. SCIENCE DRIVER: BUILDING A LIBRARY OF SUPERFLARE SPECTRA

ArgusSpec’s primary science mission will be to build a comprehensive library of superflare spectra. A stellar flare is a stochastic event, caused by the reconnecting of a star’s magnetic field lines, that releases intense

radiation across the electromagnetic spectrum.¹¹ Some active stars exhibit extremely powerful flaring events, called superflares. These are flares with energies $\geq 10^{33}$ erg, more than 10-1000 $\times$ the energy of the largest solar flare.

Intense flaring activity from exoplanet host stars can have dramatic impacts on any orbiting planets' potential habitability. The intense radiation released from superflares can reach the planets and drive photo-chemical reactions that destroy atmospheric ozone. Over time, these flares could completely remove the planets atmosphere and leave the surface vulnerable to intense UV radiation, making an otherwise habitable world uninhabitable. However, some flaring events might actually be necessary to support life on planets around cool stars, which emit very little in the UV. UV-flux has been proposed as a required ingredient for prebiotic chemistry on exoplanetary systems.^{12,13} It is possible that the necessity for low-energy flares, combined with the danger of high-energy flares, creates a flare-habitability Goldilocks zone for young cool stars that may or may not overlap with the temperature-based habitable zone.

To understand the impacts flares might have on the early evolution of terrestrial planets, and correct for the inherent bias of obtaining observations from only a handful of exceptionally active stars, a comprehensive survey needs spectroscopic observations of flaring emission from tens to hundreds of typical young stars. These observations are vital to: constrain effective flare blackbody temperatures, determine if those temperatures are accurate representations of the flare blackbody continuum, characterize the continuum and emission line evolution, and determine if flare UV emission is well described by a fit to the optical blackbody.

However, obtaining these observations can be challenging. Flares and superflares can reach peak brightness within tens of seconds and can fade dramatically within minutes; during their rapid rise and fall, they can show even shorter-timescale, complex light curve substructures.¹⁴ A spectroscopic follow-up system designed for superflare characterization should meet the following requirements:

1. **Spectral resolution of $R \geq 100$:** Observations from the follow-up system should allow for emission lines to be distinguished from the blackbody continuum, which requires only very low spectral resolution ($R \geq 100$). Operating at the minimum acceptable resolution ($R = 100$) improves SNR for faint targets.
2. **UV-Vis wavelength coverage:** Wavelength coverage should begin in the upper-UV (350 nm) and extend through the visible. Reaching the Balmer jump (364.5 nm) will help determine if a fit of the optical blackbody emission is a good predictor of UV-flux.
3. **High-cadence observations:** To capture flare substructure evolution, a follow-up system must be able to observe at 10-30s cadence while reaching a limiting magnitude consistent with seeing several flares per night from the transient event stream.
4. **Low-latency target acquisition:** The rapid rise time of flares requires a follow-up system to begin observations less than a minute after triggering on an alert. Otherwise, the system could miss important measurements of the flux and temperatures of flares at their peaks, the values which characterize the maximum blackbody UV impact on planets.
5. **Access to all-sky transient alerts:** An event stream provides the flares, and other transient events, for the system to follow-up. Alerts from all-sky, high-cadence telescopes provide the only chance of detecting significant numbers of superflares.
6. **Autonomous operation:** The follow-up system must be able to receive transient alerts, slew and acquire the target, and begin observations autonomously. It would be extremely challenging for a manual system to respond quickly enough.

With recent advancements in high-end amateur astronomy equipment, including new low-noise detectors and medium-aperture telescopes, it is possible to build a system from off-the-shelf components that meets these requirements.

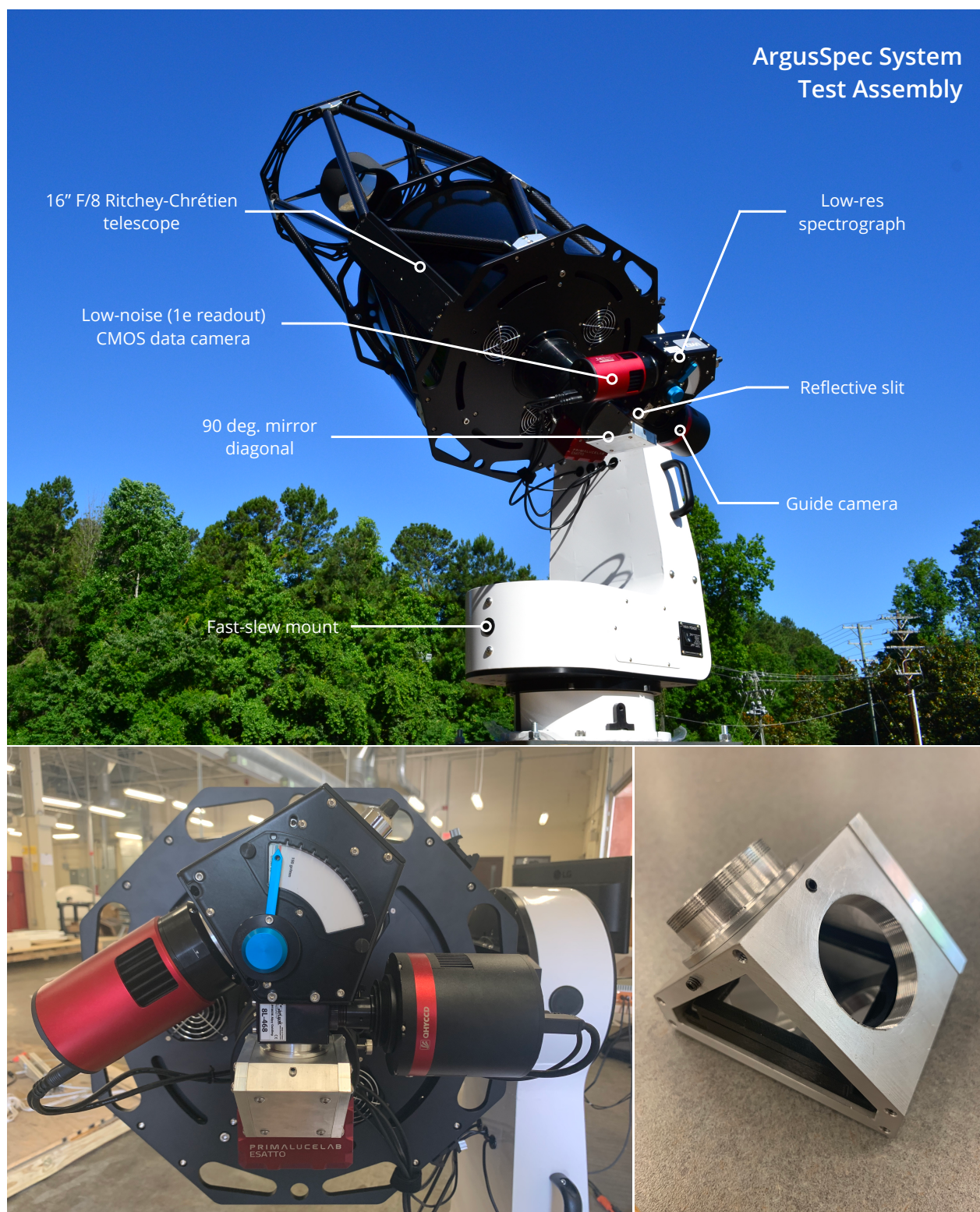


Figure 2. **Top:** A test assembly of the ArgusSpec telescope, optical train, and mount. **Bottom Left:** A close-up view of the instrumentation group. On the left is the data camera, at the top-center is the UVEX, below it is the custom-made 90-degree mirror elbow connected to the robotic focuser behind it, and on the right is the guiding camera. **Bottom Right:** A close-up of the custom-made mirror-diagonal, with one side panel removed to show the interior.

3. SYSTEM DESIGN AND PROJECT STATUS

3.1 Hardware Overview

ArgusSpec is largely built from low-cost, off-the-shelf components that are chosen to maximize limiting magnitude, observing cadence, system throughput in the ultraviolet (UV), and slewing speed within the project budget. ArgusSpec uses a 16-in F/8 Ritchey-Chrétien telescope, chosen because it has no refractive optics and therefore will have significantly better throughput in the UV. The telescope beam passes through a custom-made 90 deg. mirror diagonal ($> 85\%$ throughput over our observing spectrum), in order for the telescope back focus to be mechanically compatible with the mount, and is focused onto a $50\text{ }\mu\text{m}$ slit placed at the front of the spectrograph. The slit surface is reflective and is observed with a QHY294 Pro 11.7 MPix CMOS guiding camera for slit alignment. The guiding system has an FoV size of $11'\times 8.5'$.

ArgusSpec uses the Shelyak UVEX, which is a cross Czerny-Turner spectrograph that has been optimized for a wide range of wavelengths from the near-UV ($<400\text{ nm}$) to near-IR ($1\text{ }\mu\text{m}$). UVEX has a throughput of 35% at 550 nm, not including slit transmission, which depends on seeing conditions and telescope focus quality. UVEX allows for interchangeability between several different grating options. For ArgusSpec, we use a 150 l/mm echelette grating blazed for optimal throughput at 500 nm. The data camera, an Atik Horizon Mono II, is a 16 MPix CMOS sensor with a 21.9mm diagonal, exceptionally-low read noise (1 e^-), low dark current ($0.016\text{ e}^-/\text{pix/s}$ at -10° C), and fast readout speeds. The data camera has $3.8\text{ }\mu\text{m}$ pixels, and when paired with the low-resolution slit and grating of the UVEX, produces a raw resolving power of $R \sim 200$. However, with the low noise characteristics of the data camera, we can gain SNR by binning down in software to a resolution of $R \sim 100$, allowing ArgusSpec to observe dimmer targets. The optical train is mounted on a PlaneWave L-350 direct-drive, fast-slew mount capable of speeds of 50 deg/s . A test assembly of the optical hardware and mount can be seen in Fig. 2.

3.2 Compatibility with Evryscope and Pathfinder Transient Alert Streams

Upon deployment, ArgusSpec will receive transient alerts from the Argus Hierarchical Data Processing System using the Pathfinder instrument¹⁵ and the Evryscope Fast Transient Engine,¹⁰ which has $>98\%$ expected completeness for $m_g < 13.7$ and typical alert latencies of ~ 1 minute from detection. Limiting magnitude calculations show that ArgusSpec will be able observe targets with magnitudes of $m_V = 13$ at 10 second cadence with a SNR of 15. For brighter targets ($m_V < 11.5$), ArgusSpec's observing cadence will be an order of magnitude faster. With these limiting magnitudes, we expect the Northern Evryscope and Argus Pathfinder to detect many superflares per night that can be observed at 10 second cadence and roughly one per night at one second cadence.

3.3 Project Status

ArgusSpec is currently under development at UNC-Chapel Hill. As of the end of Q2 2022, work is almost finished on the ArgusSpec enclosure and the telescope pier is completed (Fig. 3). A test assembly of the optical train and fast-slew mount was recently completed. From a dark-sky location near our instrumentation lab in Chapel Hill, we have successfully focused the guide camera, built a pointing model using the mount, and produced test data for our pipelines. We are currently performing optical tests and calibrations on the UVEX spectrograph. We expect to complete on-sky tests of optical performance by the middle of Q3 2022. We are beginning work on the software pipelines and control interfaces. After deployment, ArgusSpec will utilize existing infrastructure built for the Argus Pathfinder at PARI to store and process data.

4. SUMMARY

The currently under-development ArgusSpec will be an autonomous, rapid-slew spectroscopic follow-up system designed to characterise transient detections from the all-sky Evryscope, the Argus Pathfinder and in the future the planned Argus Array. ArgusSpec is largely built from off-the-shelf components including a 16-in RC telescope, a low-resolution spectrograph, a high-speed, direct-drive mount, and new low-noise detectors. Within tens of seconds of detections from its companion wide-field telescopes, ArgusSpec will be able to follow up every transient in the visible sky brighter than $m_V < 13$ with 10s cadence spectroscopy. In its primary science mission, the system will build the largest library of spectroscopic superflare data to date.



Figure 3. The nearly-complete ArgusSpec enclosure, before surface protective coatings were applied. Behind the ArgusSpec container, the Argus Pathfinder is under construction. They are built in portable shipping containers so that once construction and testing is completed on both systems they can be moved to a dark-sky site at PARI.

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