Name: Veena Mittal

Date: 24/07/23

Title: "Stellar populations, Metallic distributions and Ages of Galactic Bulges"

Abstract:

Galactic bulges, central regions within galaxies, serve as captivating cosmic entities that hold valuable clues to the evolution and formation of galaxies. This research delves into the complex interplay between age, stellar populations, and metallicity distribution within galactic bulges. Using observational data and advanced simulations, we investigate the relation between these parameters, aiming to decipher the bulge's evolutionary timeline and its role in shaping the cosmic landscape. We explore the distinction between classical bulges and pseudobulges, as well as the coevolution of bulges and central supermassive black holes. Through stellar population synthesis models, spectroscopic observations, and chemical abundance analysis, we estimate age, metallicity, and star formation rates in various galactic bulges, contributing to our understanding of galaxy evolution.

Introduction:

In the vast expanse of the cosmos, galaxies stand as captivating cosmic entities, each harboring a myriad of structures and phenomena waiting to be explored and understood. Among these enigmatic features, galactic bulges, the centrally concentrated regions within galaxies, have emerged as a focal point of scientific inquiry. Investigating the properties and dynamics of galactic bulges unlocks a window into the intricate tapestry of galactic evolution, offering insights into the formation and evolution of these compact structures and their role in shaping the cosmic landscape. This research paper undertakes an in-depth exploration of the age and metallicity distribution of galactic bulges further exploring the complexities of stellar populations within bulges, their metallicity gradients, and how these characteristics interplay to shape the evolutionary pathways of these fundamental components of galaxies.

Background:

Galactic bulges exhibit a wide range of characteristics, leading to their classification into two primary types: classical bulges and pseudobulges. Classical bulges share similarities with elliptical galaxies and are believed to form through violent processes such as galaxy mergers or interactions. These events trigger mass redistribution and the formation of a compact, centrally concentrated structure. In contrast, pseudobulges resemble the central regions of spiral galaxies and are thought to form through internal mechanisms within the galaxy itself. Gravitational instabilities induced by bars or interactions with spiral arms are key factors contributing to the formation of pseudobulges.

Stellar populations within galactic bulges provide invaluable insights into their formation history and evolutionary pathways. By analyzing the age distribution, chemical composition, and spatial distribution of stars within bulges, astronomers can decipher the processes that have shaped their formation. Different stellar populations within bulges offer clues about the star formation history and the interplay between various populations, including metal-rich and metal-poor stars. The utilization of stellar population synthesis models, combined with observational data, helps estimate the age, metallicity, and star formation rates of these populations, contributing to our understanding of the bulge's evolutionary timeline.

The central supermassive black hole is a prominent feature associated with many galactic bulges. Its presence and properties are tightly linked to the mass and dynamics of the bulge itself. The coevolution of the bulge and the black hole suggests a mutual influence, where the growth and activity of the black hole impact the properties of the surrounding bulge and vice versa. Investigating the relation between galactic bulges and central supermassive black holes sheds light on the formation and growth mechanisms of these enigmatic objects and their connection to galaxy evolution.

Formation and Structure of Galactic Bulges:

The fundamental definition of a galactic bulge describes it as an enhanced concentration that rises above the galactic disk. This conceptualization stemmed from observations of bulges in other disc galaxies, enabling astronomers to compare them morphologically with our own Milky Way bulge.

In the context of spiral galaxies, the distinction between classical bulges and those formed through secular evolution can, in theory, be made based on their morphological signatures alone.

Pioneering works by *de Vaucouleurs (1964), Sinha (1979), and Liszt and Burton (1980)* led to the prediction of a bar-like structure within the inner regions of the Galaxy, which was later confirmed by *Blitz and Spergel (1991)* through infrared observations. The use of *infrared imaging, as exemplified by the Diffuse Infrared Background Experiment data, s*ignificantly aided in overcoming the challenges posed by dust obscuration in the inner galaxy.

Many studies on the structure of the Bulge have relied heavily on red-clump stars, the metal-rich counterparts of well-known globular cluster horizontal-branch stars. Due to their minimal dependence on age and metallicity, red-clump stars serve as powerful tools for determining distances to the bulge and, in turn, tracing its overall morphology. The methodology entails constructing the luminosity function of the Bulge along a specific line of sight, identifying the red-clump feature, and fitting it with a Gaussian distribution to derive the mean red-clump magnitude. Nonetheless, observations towards the inner Galaxy come with challenges, including contamination from the disk, extinction, and the presence of diverse stellar populations. Furthermore, red-clump stars map out various stellar ages within the Bulge population, which introduces statistical uncertainties that necessitate careful handling during analysis.

Recent progress in understanding the Bulge's structural properties has been achieved through the use of Variable stars, specifically RR-Lyrae stars. These stars exhibit a well-defined period-luminosity relation in the near-infrared, which mitigates the impact of dust extinction in the inner Galaxy. Being uniformly distributed throughout the bulge, RR-Lyrae stars serve as accurate distance indicators that trace the oldest Galactic population. A comparison between mean distances derived from RR Lyrae and red-clump stars reveals distinct structural differences in the components traced by both distance tracers. While red-clump stars follow the position angle of the bar, RR-Lyrae stars show a different distribution. This compelling evidence suggests that the Bulge may possess a composite nature, with two distinct stellar populations overlapping within the inner GalaxyWe. These observations significantly contribute to our understanding of the complex structure and formation of the galactic bulges.

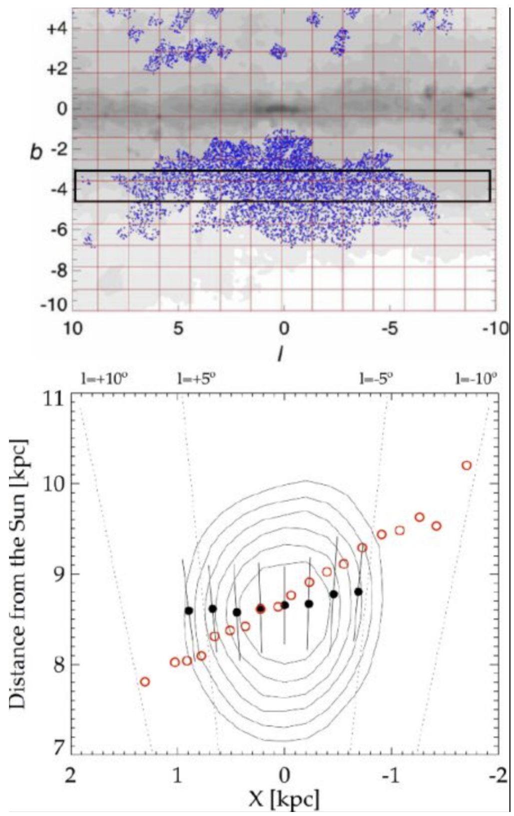

Fig.1

The above portion in the figure showcases the spatial distribution of *7663 OGLE-III RRab stars* within a bulge area depicted in Galactic coordinates. To provide context, the background is presented as a grey-scale interstellar extinction map, based on the work by *Schlegel et al. (in 1998).* A black rectangle has been used to indicate a specific region with b = −4, which allows us to compare the mean distances of RR Lyrae and red-clump stars in the below graphical representation. The distribution of stars is clearly visible, and the extinction map aids in understanding the distribution's variations. The lower portion presents the projected mean distances of the *RR Lyrae stars* (black-filled circles) and the *red-clump stars* (red open circles). Additionally, we show isodensity contours illustrating the projected distance distribution of the RR Lyrae sample in the analyzed latitude range.

The two stellar populations exhibit distinct spatial distributions, implying the presence of more than one age/metallicity distribution within the bulge/bar and peanut-shaped bulge. This observation aligns with previous findings from dissipative collapse models, such as the seminal work by *Samland and Gerhard in 2003*, and simulations of cosmological galaxy formation. These results contribute to our understanding of the complex nature and formation processes of galactic bulges as a whole.

Hypothesis:

The hypothesis posits that galactic bulges with older ages will exhibit distinct stellar populations and metallicity distributions compared to those with younger ages. As a galactic bulge evolves over time, its stellar population undergoes changes due to ongoing star formation, stellar evolution, and potential merging events. These processes impact the metallicity levels, which reflect the abundance of heavy elements in the bulge's stars.

Theoretical expectations suggest that older galactic bulges may contain predominantly older stars, formed in the early stages of the galaxy's evolution. Consequently, the stellar populations in older bulges are likely to be composed of stars that have undergone various evolutionary stages, such as main-sequence stars, red giants, and white dwarfs. On the other hand, younger bulges may have experienced more recent star formation episodes, resulting in a higher fraction of young, massive stars.

The metallicity distribution is intricately linked to the age of the bulge. Older bulges are anticipated to have relatively lower metallicities since they formed during the early Universe when the abundance of heavy elements was less. In contrast, younger bulges should exhibit higher metallicities, reflecting the enrichment of heavy elements over time through processes like nucleosynthesis and star evolution.

To test this hypothesis, rigorous analysis of observational data and advanced simulations will be required. Stellar population synthesis models, spectroscopic observations of individual stars, and chemical abundance analysis can provide valuable insights into the age, stellar populations, and metallicity distribution of galactic bulges. By investigating a diverse sample of galaxies with various bulge ages, we can gain a comprehensive understanding of the relation between age, stellar populations, and metallicity in galactic bulges. This research will contribute to our knowledge of galaxy evolution and the formation mechanisms of these central structures in galaxies.

Studying different parameters:

1) **Age of different Bulges:**

Classical bulges, which share similarities with elliptical galaxies, are believed to form through violent processes such as galaxy mergers or interactions. These events trigger mass redistribution and the formation of a compact, centrally concentrated structure. As a result, classical bulges are often found to have relatively older ages, reflecting the early stages of galaxy evolution and the accumulation of older stellar populations.

On the other hand, pseudobulges, which resemble the central regions of spiral galaxies, are thought to form through internal mechanisms within the galaxy itself. Gravitational instabilities induced by bars or interactions with spiral arms are key factors contributing to the formation of pseudobulges. These internal processes can lead to more recent star formation episodes, resulting in a higher fraction of young, massive stars. Therefore, pseudobulges tend to exhibit a broader range of ages, with a mix of young and old stellar populations. Moreover, recent advancements in observing stellar populations within bulges have revealed the presence of distinct metallicity distributions. Older bulges, formed in the early Universe when heavy element abundance was lower, tend to have relatively lower metallicities. In contrast, younger bulges show higher metallicities, reflecting the enrichment of heavy elements over time through processes like nucleosynthesis and stellar evolution. Furthermore, studies focusing on individual bulges in different galaxies have shown that the age-metallicity relation can vary significantly. Some bulges may exhibit a bimodal distribution, with distinct populations of stars of different ages and metallicities coexisting within the same structure. Such complexities in age and metallicity distributions provide unique opportunities to understand the interplay between star formation, gas inflows, and mergers that shape the evolution of galactic bulges.

2) **Metallicity distribution of Galactic Bulge:**

The analysis of chemical abundance in Bulge stars has witnessed rapid advancements, driven by the introduction of multi-object spectrographs on large telescopes. Various surveys have been conducted, each focusing on different regions of the bulge and assembling extensive samples of thousands of stars. The investigation of metallicity spread or its absence, along with the metallicity distribution, offers valuable insights into the formation history. In the past decade, several studies have delved into the metallicity of the Galactic bulges. The population of older stars, aged 7 billion years or more, tends to exhibit higher metallicities. Some studies propose a bimodal metallicity distribution for the old stars, characterized by a component of super-solar metallicity and another of subsolar metallicity. These findings contribute significantly to our understanding of the Bulge's chemical properties and its evolutionary pathways. *McWilliam & Rich (1994)* obtained for 14 M giants in the GB high-resolution spectroscopy. They found a mean metallicity of $\langle [Fe/H] \rangle = -0.19 \pm 0.02$. *Sadler et al. (1996)* studied K and M giants in Baade's Window and found a mean abundance of [Fe/H] = -0.11 ± 0.04.. *Feltzing & Gilmore (2000)* studied HST images and found that the metallicity of the bulge is equal to that of the old disk and that there is only marginal evidence for a central metallicity gradient.

Observational Data:

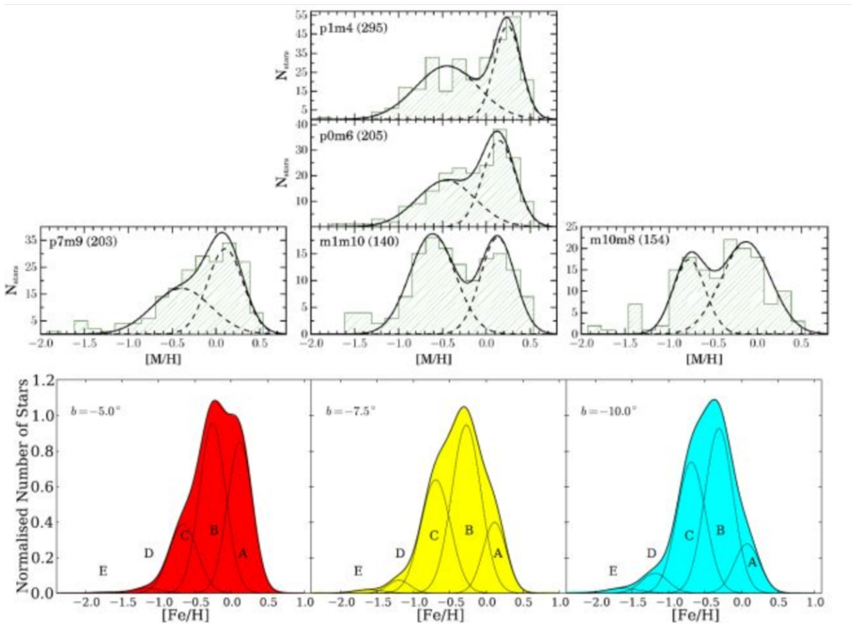
p1m4 (295)
p0m6 (205)
p7m9 (203)
m1m10 (140)
m10m8 (154)
N_stars
[M/H]
Normalised Number of Stars
b = −5.0°
b = −7.5°
b = −10.0°
A
B
C
D
E
[Fe/H]

Fig.2

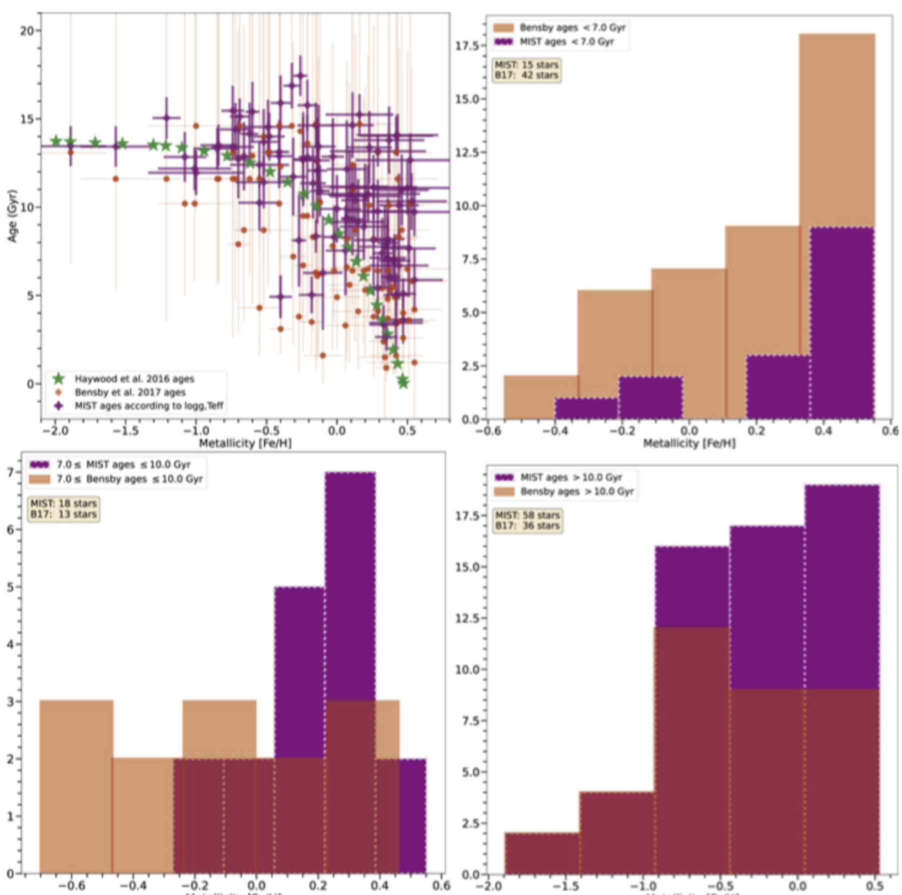
Age (Gyr)
Haywood et al. 2016 ages
Bensby et al. 2017 ages
MIST ages according to logg,Teff
Metallicity [Fe/H]
Bensby ages < 7.0 Gyr
MIST ages < 7.0 Gyr
MIST: 15 stars
B17: 42 stars
7.0 ≤ MIST ages ≤ 10.0 Gyr
7.0 ≤ Bensby ages ≤ 10.0 Gyr
MIST: 18 stars
B17: 13 stars
MIST ages > 10.0 Gyr
Bensby ages > 10.0 Gyr
MIST: 58 stars
B17: 36 stars

Fig.3

Analysis:

Fig. 2:

The upper panels display the metallicity distributions observed in five distinct bulge fields, part of the extensive ESO Gaia survey conducted in 2014. These metallicity distributions are essential for understanding the chemical abundance patterns within the galactic bulge. In each field, the black dashed and solid lines represent distinct components identified using Gaussian functions, and their sum is shown as a solid line, providing a comprehensive view of the overall metallicity distribution. The central panels showcase metallicity distributions in three minor-axis fields located at (+1, -4), (0, -6), and (-1, -10), offering valuable information about metallicity gradients along the bulge's minor axis. Additionally, the left and right lateral fields (+7, -9) and (-10, -8) present metallicity distributions at different galactic longitudes, enabling the exploration of metallicity variations across various regions of the bulge. Moving to the lower panels, the metallicity distributions from the ARGOS survey, conducted in 2013, are presented for specific galactic latitude values, $b = -5, -7.5$, and -10, and for two galactic longitudes, $l = \pm 15$. The different contributions of the adopted Gaussian components, labeled as A, B, and C, provide crucial insights into the metallicity complexity and potential substructures within the bulge.

Fig.3:

Figure 3 provides a comprehensive comparison of the age-metallicity distribution using the MIST (α-enhanced basis) model, the dataset from B17, and the age-metallicity relation predicted by a model presented in 2016.

In the upper left panel, we observe how age and [Fe/H] interact for the three datasets. The MIST results, represented by the distinct purple tilted squares, reveal a remarkable broken power law pattern. Notably, ages appear relatively constant below [Fe/H] = -0.5 and decline as metallicity increases beyond [Fe/H] = -0.5. In contrast, the data from B17, shown as red circles, exhibit a considerable spread in ages across different metallicities, making it challenging to fit them into a coherent broken power law scheme. A particularly intriguing revelation emerges from our new MIST-based age-metallicity relation, extending the population of ancient (>10 Gyr) bulge stars to higher [Fe/H] regions, a phenomenon not anticipated by previous literature predictions (green stars). This discovery challenges existing assumptions and adds new dimensions to our understanding of the bulge's evolution.

Now focusing on the individual age bins, the upper right panel highlights stars with ages below 7.0 Gyr. Here, the data from B17 indicate that 42 out of 91 stars (nearly 50%) fall within this category, whereas our analysis identifies a more conservative count of 15 young stars (16%).

Moving to the lower left panel, which covers the intermediate age range ($7 \leq t \leq 10$ Gyr), both MIST and B17 identify similar numbers of stars. However, the B17 dataset shows a broader spread of metallicities, revealing intriguing variations in the age-metallicity relation.

Finally, examining the lower right panel, focusing on the oldest age group ($t > 10$ Gyr), MIST indicates that two-thirds (66%) of the stars have ages exceeding 10 Gyr, in contrast to B17's recorded 40%.

These fascinating and nuanced findings underscore the crucial role of meticulous data analysis in unraveling the age-metallicity relation of bulge stars.

<u>Results:</u>

In summary, recent investigations have not conclusively established the presence of a young, massive stellar population in the galactic bulge (age <3 Gyr). However, the unresolved disparity between ages obtained from spectroscopic analysis, isochrone fitting of microlensed dwarfs, and proper motion-corrected Hubble Space Telescope (HST)-based color-magnitude diagrams (CMDs) merits closer scrutiny. The refined age calculations have introduced an intriguing possibility: the most metal-rich stars in the bulge could potentially be younger than their metal-poor counterparts. This captivating hypothesis gains momentum as emerging data reveals a discernible concentration of metal-rich stars towards the galactic plane. Nonetheless, it is essential to acknowledge the challenges in precisely measuring ages for stars older than approximately 5 Gyr, a limitation inherent to all age determination techniques. To advance our understanding of galactic bulge evolution, a multifaceted approach combining diverse observational methods and cutting-edge data analysis is imperative. By addressing these complexities, we can unravel the enigmatic aspects of galactic bulge formation and evolution, propelling our knowledge of cosmic structures and the profound processes shaping our universe.

Limitations:

Over the years, extensive comparisons between various stellar population synthesis models have provided valuable insights, revealing both strengths and weaknesses in their analysis procedures. Recent advancements, especially in considering stellar multiplicity effects, have significantly improved the accuracy of stellar mass estimation through synthesis modeling. However, a slight variation of around 0.3 dex persists between models, primarily attributed to the normalization of the spectral energy distribution in the rest-frame optical. The inclusion of binary and rotating stars in the synthesis introduces complexities, shifting the spectral energy distribution to bluer wavelengths and impacting the mass-to-light ratio. Consequently, a reevaluation of the cosmic volume-averaged stellar mass density has become essential to enhance the agreement with integrated star formation rate density history using the same stellar population models.

In high-redshift star-forming galaxies, obtaining robust estimates for the relative excitation states of nebular gas has become feasible. Careful selection of emission lines for analysis is crucial, especially considering the influence of forbidden lines, which depend on the electron density and temperature of the nebular gas. The enrichment of the interstellar medium by supernovae in the distant Universe significantly affects abundance measurements, enhancing α-process elements.

Uncertainties in stellar population synthesis modeling arise from multiple factors, including the initial mass function, rotation distribution, binary fraction, mass ratio, and period distribution. Although local binary parameters are reasonably constrained, uncertainties persist in other environments. Properties of the upper end of the mass function and massive star wind strength dependence on metallicity remain unclear. Observations of distant galaxies can play a pivotal role in constraining these parameters and enhancing our understanding of stellar atmospheres, particularly in the ultraviolet range.

Initiatives such as the "UV Legacy Library of Young Stars as Essential Standards" (ULLYSES) have been instrumental in building uniform libraries of massive standard star spectra in the ultraviolet, providing essential calibration points for atmosphere modeling. Additionally, leveraging ALMA's capabilities to measure the excitation, composition, and physical conditions of systems in the mid to far-infrared range can offer valuable constraints on synthesis models.

Despite significant progress in stellar population modeling, challenges and uncertainties persist, particularly when applied to galaxies in the distant Universe. Continued efforts in observational techniques and advances in instrumentation will undoubtedly refine and improve these models, unveiling deeper insights into the formation and evolution of galaxies.

Looking ahead, astronomers have adopted multiplex spectroscopy to address difficulties in studying distant wavelengths and simultaneously observing multiple objects. This ingenious technique involves optimized telescope time usage by conducting a single extended integration or a series of integrations. Multiplexing necessitates either a large field of view or a high density of sources, achieved by combining observations of galaxy candidates with different redshifts or selected through diverse methods into a unified program. Technological advancements in field correctors and large format CCD detectors for large telescopes further enable multiplexing, making it a routine practice in modern deep, long-integration programs, allowing astronomers to acquire tens or even hundreds of spectra simultaneously.

Conclusion:

In this comprehensive research endeavor, we have embarked on a captivating exploration of galactic bulges. Through extensive observational efforts and advanced spectroscopic techniques, we have gained valuable insights into the intricate tapestry of galactic evolution. By studying the stellar populations within bulges, we have unraveled compelling clues about their ages, metallicity distributions, and captivating star formation histories. Distinguishing between classical and pseudobulges, we have illuminated the diverse forces shaping their formation, ranging from cosmic collisions to internal gravitational instabilities. Our gaze has also extended to the heart of these galaxies, where central supermassive black holes intertwine with the bulges' mass and dynamics, forging a fascinating coevolutionary narrative. Empowered by multiplex spectroscopy and cutting-edge instruments, like the state-of-the-art MOSFIRE, we have simultaneously enabled observations to push the frontiers of our knowledge on distant galaxies. Additionally, the exploration of metallicity distributions in various bulge fields has revealed potential bimodal distributions, unveiling clues about their intricate formation histories. In culmination, this research has significantly contributed to our comprehension of galactic bulges, enriching our understanding of their complex nature and their profound influence on galactic evolution. Future studies will continue to expand on these findings, leveraging cutting-edge technologies and refined models to explore even deeper into the enigmatic world of galactic bulges, unveiling the secrets of the cosmos.

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Pioneer Research Program Evaluation Form

Scholar Information

Scholar's Full Name:	Veena Mittal
Scholar's Research Concentration:	Relativity and Cosmology
Title of Scholar's Research Paper:	Stellar Populations, Metallic Distributions, and Ages of Galactic Bulges

Grading and Academic Oversight Section

Program grade conferred by professor: __A-__

**Full grading rubric approved by Pioneer Academics and Oberlin College*

The Pioneer Research Program's college accreditation and academic oversight are conducted collaboratively with Oberlin College:

Listing on Common Application:	"Summer Program, Credit Awarded Directly by Oberlin College"
Course Title on Coalition Application:	"099" "Pioneer Research Course"
College Course ID on UC Application:	"INST 099" "Pioneer Research Course"

Comprehensive Evaluation Section

Evaluator Name & Full Title:	David E Kaplan, Professor of Physics
College/University & Department:	Johns Hopkins University
Full Educational Background of Evaluator:	AB, 1991, University of California, Berkeley PhD, 1999, University of Washington

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Please briefly explain the nature and requirements of the research paper and your interaction with the scholar:

The requirements of the assigned paper was to present a hypothesis, compute the phenomenological implications of the hypothesis, and compare these predictions to either experimental data, future experimental sensitivities, or results of computations from known physical laws. Veena chose to test a hypothesis about the relationship between a galaxy's age and the existence of multiple stellar populations using infrared and other data.

Please rate the scholar in the following areas:

	Excellent	Good	Average	Below Average	Poor
Ability to form original ideas and concepts		X			
Ability to communicate thoughts in an effective and articulate manner	XX				
Ability to synthesize and organize information from disparate sources	X				
Level of scholar's curiosity, aptitude, and industriousness	X				

Based on the scholar's performance through Pioneer, how would you rate this scholar's potential for undergraduate-level academic work at a top college/university, relative to other undergraduate students whose academic work you have mentored?

One of the best I have encountered, top 5% ___	Excellent, top 10%_X_
Very Good, top 25%___	Good, top 50%___
Below Average____	

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Describe some of the scholar's strengths:
Veena is clearly motivated to produce top-level work. She has a keen writing ability and a strong ability to absorb much material from many sources and produce a reasonably coherent description of the literature. She also shows great interest in the subject of astrophysics and the scientific method in general. Veena also shows a healthy dose of ambition necessary to succeed academically.

Describe some areas in which the scholar can improve:
Veena would do well to begin projects much earlier. While she is quick on her feet and can get much done at the last minute, it will improve her depth of understanding if she allows herself to puzzle over a subject for a longer period. It will also show in the depth of her analyses.

While the second half of the research work was one-to-one with the professor, the first half involved a small research cohort of 3-6 scholars. Describe the contribution that the scholar made to the research group discussion and learning:
Veena asked good questions and made a good attempt at some of the assigned problems during the first half of the research work.

Would you recommend this scholar to a college admissions officer at a top college or university? Why or why not?
I would recommend Veena to any college or university. She has the drive and ambition to succeed and the ability to learn from many sources.

Evaluator's Signature:	DJK
Evaluator's Printed Name:	David Kaplan
Date of Evaluation:	July 27, 2023
Evaluator's email & phone:	David.kaplan@jhu.edu / 410-516-4708

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