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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2024 February 9 at $16^h\ 00^m$
in the Geological Society Lecture Theatre, Burlington House

Mike Edmunds, *President*
in the Chair

The President. Welcome to the monthly A and G Highlights Meeting. This is a hybrid meeting and questions can be asked at the end of the lecture but you will be muted so please use the chat facility. Questions will be read out by the Assistant Editor of *Monthly Notices*, Dr. Pamela Rowden.

The Crafoord Prize in Astronomy has been won by three of our Fellows: congratulations to Douglas Gough (Cambridge), Jørgen Christensen-Dalsgaard (Aarhus), and Connie Aerts (Leuven). They have been awarded the Prize by the Swedish Academy of Sciences for their work on asteroseismology, so very well done to them.

On to today's programme. I'm very glad to welcome Dr. Laura Hayes to talk about 'The active Sun'. Dr Hayes is a solar physicist at the European Space Agency. Her research focusses on the high-energy processes in the solar atmosphere and the impact of solar flares on space weather. She completed her PhD at Trinity College, Dublin, in 2018 and furthered her postdoctoral work at NASA's Goddard Spaceflight Center in the USA until 2021 before joining ESA as a research fellow.

Dr. Laura Hayes. [*Solar Orbiter*, a mission launched in 2020 by the European Space Agency in collaboration with NASA, aims to study our complex and dynamic closest star, the Sun. Embarking on a unique trajectory, the mission approaches the Sun as close as 0·28 astronomical units (AU) during its perihelia, providing unprecedented observations of the solar atmosphere and its polar regions. This talk introduces the mission's objectives and design, presents the latest scientific results from *Solar Orbiter*, and highlights its contributions to understanding solar processes, including solar-wind origination and magnetic-field dynamics. Furthermore, the discussion will extend to how *Solar Orbiter*'s findings are being integrated with data from other missions and ground-based observatories across the heliosphere, such as the *Parker Solar Probe*, *SDO*, and *DKIST*, opening new avenues for comprehensive solar and space-weather research.]

The President. Thank you very much, indeed. *Solar Orbiter* has gone very near the Sun — has there been any deterioration in the spacecraft? Is it armour-plated sufficiently so that it doesn't degrade?

Dr. Hayes. This was one of the technological constraints of putting a mission close to the Sun. It is designed with the Solar Black material to protect it as it is going in close. To date we haven't seen any major degradation; of course there are little things but nothing unexpected.

The President. Any startling results? You've given us a general overview. Has it made a major contribution to understanding any of the processes?

Dr. Hayes. It has opened up more questions, which is always a good thing. In terms of discoveries, about finer-scale things we have seen which we call campfires — really small events in the solar atmosphere: the question is whether they contribute to the heating of the solar corona — we don't understand why it gets so hot. There have been some really nice results regarding the origin of the source of the solar wind.

Professor Mark Lester. I just wondered — those small fires: do you see them develop and grow into larger events, or do they always remain at roughly the same scale?

Dr. Hayes. From my understanding we don't see them grow into very large events, but it is a distribution so you have very few large events and the question is how far does that distribution go back. Is it the same physics that is going on in the smaller events and the larger ones? I think that the jury is still out on that, but there might be someone in the room who disagrees with me.

Ms. Ana Vitiello. Can you please tell us if there is a very strong wind, how fast can you act to prevent damage to the satellite?

Dr. Hayes. Usually when you have a large eruption like that there are two components. The solar flare, which is light, and which takes eight minutes to reach Earth, has a dramatic effect on telecommunications. The event we usually associate with that is a coronal mass ejection which really has an impact on our satellites and typically that reaches us within 1 to 2 days and we can mitigate that. The first thing we ought to do is to try and mitigate that. We haven't seen a very dramatic one in a long time. We want the solar flare to happen, but we don't want the consequences!

The President. Be careful what you wish for! Any further questions? If not, thank you very much [applause].

Our next talk is about 'The origin of metals and dust within galaxies in the first billion years of cosmic time' and it will be given by Dr. Joris Witstok. Joris is a Dutch astrophysicist who completed his undergraduate studies at Leiden; he moved to the University of Cambridge for his masters degree which he did on the numerical simulation of diffuse emission from the cosmic web; and undertook doctoral studies under the supervision of Renske Smit leading to research in the astrophysics of star formation within the first galaxies, using facilities such as *HST* and the *Atacama Large Millimeter Array*. He defended his thesis in 2022: 'Spectroscopic studies of star-forming galaxies and the intergalactic medium in the early Universe'. He is currently working as a PDRA at Sidney Sussex College and the Kavli Institute for Cosmology in Cambridge where he continues to explore the distant-galaxy frontier as a member of the *JWST NIRSpec*-spectrograph guaranteed-time-observation galaxy-assembly team. So, here to assemble some galaxies for us, please welcome Dr. Witstok.

Dr. Joris Witstok. What do we know about the early part of the evolution of the Universe? The epoch of re-ionization is the period in which I am most interested — the first billion years of cosmic time. The Dark Ages is the epoch when some of the dark matter (DM) begins to assemble into haloes which then host some of the first galaxies. This is where the cosmological model called ΛCDM has been hugely successful in allowing us to explain how we can get galaxies to form inside these DM halos. Cosmic dawn marks the formation of the first stars and galaxies and this is a huge milestone. Stars begin to emit lots of highly energetic ionizing photons — sufficiently energetic to ionize hydrogen which is largely neutral at this time. These first stars quickly explode as supernovae which then spread metals out into the Universe. I want to concentrate on this epoch and to show how the metals produced can be converted into dust — solid metal grains. What we wish to know is what does the metal and dust content of these first galaxies look like?

Just before the launch of *JWST* we thought that galaxies had blue stellar-continuum slopes and low stellar masses and that this points to minimal dust obscuration. These galaxies are also characterized by having metal-poor ionized gas. With the facilities such as *JWST* we can look anew at this. From the ground we could reach $z = 3{\cdot}5$ and were limited by atmospheric transmission, whilst if looking at the Ly-α line the limit was $z = 6$ or 7. Two of these facilities are *ALMA* and *JWST*. With *ALMA* we can see some metal transitions in the far IR whilst with *JWST* we can look at the UV and optical light of these galaxies. I want to talk about the project I have been working on. It is called the JADES survey and stands for *JWST* Advanced Deep Extragalactic Survey which is a joint effort between the teams running *NIRCam* and *NIRSpec* which are the main camera and spectrograph on *JWST*. Our website (http://jades-survey.github.io) has an interactive view of all the imaging we have done with *NIRCam*. Some of the target galaxies have exposure times of up to 30 hours on single targets, which gives us an unprecedented sensitivity limit. In 2017 our best data with ground-based facilities was on a $z = 8$ galaxy where a doublet of emission lines is just visible. Contrast this with a *NIRSpec* spectrum covering 1–5 microns and reaching $z = 10{\cdot}6$, and the spectrum is covered in features. It appears to have an AGN and therefore already houses a supermassive black hole in its centre. One galaxy appears to have formed just 300 million years after the Big Bang — we will follow this up by observations with *ALMA*.

What can we say about the metals inside these objects? Plotting O relative to H as a function of the galaxy mass, the local galaxies follow a tight relationship. The tighter this is the more metals are present, so the graph represents galactic evolution. With the new *JWST* data, the normalization decreases but we see the relation does extend to earlier times. Two galaxies at $z = 7$ appear very red and have high extinction which indicates a lot of dust. They have lots of stellar mass and high metallicity — all present within the first billion years. What do we know about how the galaxies bring up their metals and dust, since clearly they are able to do this rather efficiently?

Dust is a crucially important part of galaxy evolution in the sense that on the small scale it stimulates star formation by forming molecules and allowing gas clouds to fragment into smaller clouds, but for us observers it is annoying because it obscures our view of this process. It absorbs mostly in the UV and optical and re-emits thermally in the IR. We need to take this into account when doing our measurements.

If we look at the galaxy spectrum, in the UV the dust 'flattens' the spectrum there, and this is what *JWST* is able to see. Using *ALMA* we can directly detect the far-IR energy distribution, where the dust is thermally re-emitting. Features include emission from certain molecules, most importantly polycyclic aromatic hydrocarbons (PAHs) with a large peak indicating the cold-dust component. Even at $z = 8$ there are reservoirs of dust up to 10^8 solar masses surrounding these galaxies. This implies stars have to form and produce metals which condense into dust grains within a few hundred million years. What we also see, if we measure the temperature of the dust as a function of z or cosmic time, as we get to the early Universe, the dust temperature increases a little but not as much as previous models have predicted. The cooler the dust, the harder it is to observe. This is posing a challenge for current models. When we look at typical interstellar conditions, the density of the interstellar medium, the density at high redshift is forty times that at $z = 0$.

To explain the dust build-up, models invoke SNe and AGB stars whose winds create an environment for dust formation or even the direct growth of grains inside the interstellar medium. If we look at dust mass as a function of stellar mass we should be able to predict, given some amount of stars in a galaxy, what is the maximum amount of dust that a galaxy can produce. We also need to look more carefully at the properties of the dust grains. We measure the absorption and extinction in the optical and IR as a function of wavelength. Using stars in the Milky Way and the Magellanic Clouds of known spectral types we can determine how much light is obscured by dust, but obscuration and attenuation varies greatly in the Milky Way. There is a significant peak in the extinction curve at 2200 Å, known as the UV bump, thought to be due to carbonaceous dust. One promising candidate is PAHs — they are mainly formed by AGB stars. The most massive galaxies are very bright in the mid-IR and contain relatively many PAH molecules. In the UV those very same galaxies have a very strong absorption feature, so PAHs are very much correlated with this absorption feature. If these are formed in the most massive galaxies over a long time can we see this in the first generation of galaxies? — presumably not, but it provides a nice test case of SN and AGB-star dust production.

We can see this feature very early on and the galaxy in our press release from the JADES survey shows a strong absorption at 2175 Å. The data from *NIRSpec* allows spectra to be taken in the rest-frame UV and optical up to $z = 10$. One conclusion — either SNe or WR stars, both of which are potential dust sources, are able to produce dust on very short time-scales, as evidenced by a binary pair of WR stars which leave behind a multi-ring structure as they orbit. Recently a $z = 12{\cdot}5$ galaxy was observed by the *JWST* with 100-hours' exposure time. We finally managed to observe some of the emission lines which contain a lot of carbon and it is shining a light on what is happening in the very early Universe.

The President. Thank you very much. Can I invite questions?

Reverend Garth Barber. Could these very early advanced features be an indication of early dark energy, that the Universe is actually older than the present model?

Dr. Witstok. I think at this point we can't definitively prove or disprove any cosmological models. We first have to dig into the astrophysics and see if we can understand these sources responsible for the production of dust because there is a lot of uncertainty there. Even in local galaxies we are sometimes struggling to match the number of stars. With the amount of dust we see, I think there is some more work to be done on our side and then we can turn to the cosmologists and tell them that their model is wrong.

The President. There is a question on-line.

Dr. Rowden. This question comes from Gavin James. He asks "You suggest that dust has formed more quickly than might be expected. *JWST* observations also show that more galaxies are formed at higher redshifts than expected. What is your take on the accuracy of the current estimate of the age of the Universe?"

Dr. Witstok. It comes back to the same question. It is true that with *JWST* we have seen, for example, galaxies are around much earlier and are much more abundant than we might have expected before, but I think that first we have to see within the context of astrophysics there is a lot going on with how a galaxy forms, and how it builds up its stellar mass. There is definitely some room in the models there to try and explain how the galaxies are already in place quite early on. I think that at the moment this very much fits in with the ΛCDM models having an age of about 13 billion years.

The President. Don't panic!

Professor Ian Robson. In the 1980's there was a big bandwagon on polycyclic aromatic hydrocarbons (PAHs) explaining everything in terms of 2175 Å and spectral features in the infra-red, and yet Bruce Draine said in his review that this was inconsequential and that it was not conclusive, so what has happened now?

Dr. Witstok. I should say that I am not an expert in PAHs myself. I think that PAHs are the most important dust species in terms of the number of features and how they can explain some of the observations especially in the mid-IR. Most of the peaks in these spectra we are confident were produced by PAHs so they are definitely a very important component of dust as a whole. I think there are still a few details to be confirmed.

The President. What would worry me a little is that your very distant galaxy's spectrum did not look like a normal PAH feature. It was not a nice peak — in fact, it was rather messy. Should we begin to panic at that? Could it be something else?

Dr. Witstok. The feature that we are seeing is actually in the UV so the absorption by the same dust grains — these are the emission features.

Professor Richard Ellis. I don't understand this puzzle that dust forms so quickly. It is natural that if you go to the very early Universe there are probably lots of massive stars with low metallicity. They explode within five million years, and if we look at something like SN 1987A it produced half a solar mass of dust. Turning to this issue of why galaxies are so bright at this early time, one of the leading hypotheses is that they are sending out their dust that is already there. Is it a surprise that the Universe is dusty at such an early time?

Dr. Witstok. I would agree. It is not a surprise that it is dusty. The numbers that we see are starting to feel a little uncomfortable. On one of the plots I showed that we are starting to exceed even the most optimistic SN yields, so every SN would have to produce one solar mass of dust and not destroy any of it in the reverse shock.

Professor Ellis. But that is for some classic IMF.

Dr. Witstok. I agree — we definitely expect dust to be there.

Professor Steven Eales. Could you say a little more about the C/O ratio that you were talking about, because that is really interesting?

Dr. Witstok. There is recent work by Francesco D'Eugenio. As I mentioned, this is one of the deepest spectra we have taken so far and we can clearly see the C III doublet and also C IV is not detected significantly, but if we compare these abundances it points out the super-solar C/O ratio.

Professor Eales. Is that the opposite of what you would expect with normal stars?

Dr. Witstok. Yes.

Professor Eales. Do Population III models always predict a super-solar C/O?

Dr. Witstok. What I can say is that if you look at some of the most metal-poor stars in the Milky Way, they actually tend to be relatively carbon rich. This might be the direct enrichment of the Population III SNe.

The President. One last question on-line and then we must move on.

Dr. Rowden. This question comes from Sanjeev Kalita who asks "Can we explain high-z dust by shifting the Big Bang (alternative to ΛCDM), or can early Population III explain that?"

The President. That's the same question.

Our next talk is 'Our fragile space — protecting the near-space environment' and it is part of a photographic exhibition and engagement project. Our environment is a great concern for the RAS both for Earth observation and for satellites and for the implications for ground-based and space-based radio and optical observation. It is a very serious problem. We fire off letters, angrily, to lots of places and try to put pressure to get some kind of international regulation. It's a great pleasure to welcome Max Alexander who is a well-known friend of the RAS, whom I have known for many years. He is an international photographer and a creative strategist — I'm sure he'll tell us what that is, probably [laughter]. He specializes in science communication through visual storytelling. His passion for understanding the Universe and making it meaningful to others has motivated him to work in this arena. He has a diploma in astronomy from UCL and he is a Fellow of our Society. He freelances for numerous prestigious organizations around the world including the UK Space Agency, ESA, ESO, SKAO, book publishers, and magazines. He has photographed Nobel prize-winners, astronauts, and world leaders. He has had two science exhibitions at the Royal Albert Hall — 'Explorers of the Universe' and 'Illuminating Atoms'. His work for the UK Space Agency has involved photographing the ESA/British astronaut Tim Peake and includes documenting his Soyuz training, which must have been quite fun, and also providing him with photographic training for his work aboard the *ISS*. Max proposed an international asteroid day sanctioned by the UN, and he is also photographer-in-residence there. Please give a warm welcome to Max Alexander [applause].

Mr. Max Alexander. I want to talk about the exponential growth of satellites and mega-constellations, and the increasing amount of space debris. The starting point for me is astronomy. I have been working on these topics for three years including a year-long photography project. It's about three key things. How do we benefit from the use of space? What about the loss of the night sky and space sustainability — world projects and initiatives and regulation? I am doing reportage and portraits because it is important to tell the human story.

The photographic exhibition was hosted on the Underwriters Floor at Lloyds of London, because they are concerned about the risks, and it was opened by the astronaut Tim Peake.

Geostationary satellites are traditionally three Earth-diameters out but they are getting closer to Low Earth Orbit (LEO) and so thousands are needed to cover the Earth.

Three months after the end of the exhibition there was a round-table discussion at Lloyds. At the opening exhibition, standards for space sustainability were announced and amongst those attending were the Science Minister George Freeman, the CEO of Lloyds, and other senior personnel. Amongst the topics discussed were the benefit of space for telecommunications — the biggest provider of such services currently is SES of Switzerland. The conversation about mega-constellations was mainly about the internet, but financial services were thought to be just as important. Fifty per cent of arable farmers in the UK use satellite information and world-wide 18% of the economy is reliant on the use of space. This includes *Sentinel-5*, an instrument built by Airbus in Stevenage which is monitoring trace gases in the atmosphere. In addition, more than 50% of climate-change monitoring is done from space.

Turning to anthropogenic change — plastic in the ocean is a good analogue for what is going on in space since it has been dumped there for 65 years. It's now starting to happen in space — 47% of the material there is aluminium and this amounts to about 10 000 tons, but the velocity and momentum that it possesses is the danger factor. The UK Space Agency just commissioned a large report of the effect on the Earth's atmosphere of satellites de-orbiting. US Air Force studies of the upper atmosphere show traces of aluminium (10%?) which can only have come from satellites. A study in Iceland last week showed that in 10 to 30 years from now such events could affect the Earth's magnetic field. Another potential example of anthropogenic change is the appearance of noctilucent clouds 80-km high in the atmosphere which have been around since the industrial revolution — another example of the effect of human activity.

I have been to Chilbolton where they do satellite tracking — they are re-purposing some of their time and telescopes for tracking space debris and satellites. At Astrofest last weekend Robert Massey talked about work at Jodrell Bank and the substantial effect of satellites in radio wavelengths. The RAS is playing a leading role, in co-operation with Starlink and SpaceX.

The first recorded piece of space debris is in a Paris museum. It is a part of an Ariane 4 rocket which is three to four stories tall and ended up in Mongolia. Every time I was in a clean room, a space company, or a museum at ESTEC I cleaned out the cabinets and photographed examples of what is in space — solar panels, boom arms, fuel tanks, or the chassis of cubesats.

At the University of Kent they are doing ballistic tests, firing 3-mm plastic pellets at twice the muzzle velocity of a rifle into a piece of copper, but velocities in space are five to ten times the muzzle velocity of a rifle. A *Hubble Space Telescope* solar panel that was retrieved during a servicing mission was brought back to Earth to show the impacts sustained as a result of being in orbit. Donald Kessler has speculated on the possible domino effect if a satellite collided with another and the resulting fragments went on to impact other satellites.

I visited Vandenberg Air Force Base in California where I saw a Starlink launch with 40 or 50 small satellites on board. I flew overnight to Cape Canaveral where I observed two further launches. Last year more than 200 launches were approved and so the cost of satellites is coming down.

Increasingly, more military installations are being re-purposed for tracking space debris. In Madrid they have been tracking debris for 50 years and will continue to do so for years to come. On Tenerife, ESA can track satellites fitted with mirrors using lasers. Eventually they expect to be able to move satellites.

Professor Mini Rai on an all-party Parliamentary scientific committee has been given a £28M grant to develop robotic satellite catches. This is difficult to do as you have to match the rate of tumble. Another method is to use solar sails to de-orbit satellites. A Swiss company called Clear Space One has a £12M grant from the UK to develop this technology. Another line of development is the use of non-toxic materials in space instruments — Japan has, for instance, used wood in a satellite.

Reusing and refuelling satellites is also an idea that is being worked on. A Welsh company is looking at ways of de-orbiting satellites and recycling them.

A sub-committee in Vienna is working on the legal aspects of space. They are working on financial and economic incentives for companies to act responsibly. We need to get the Government on-board to incentivize the investors. The UK is playing a leading role here.

The President. Thank you, Max. Beautiful photographs. There is a very deep message that you are trying to get across. Questions and comments? I think that the important point you make is that there is so much money tied up in this internationally that unless you can get the money men involved, it is not going to happen.

Mr. Alexander. That is the key and getting the investors to invest only in those projects that reach these standards.

Professor Roger Davies. A lot of people model the Earth's atmosphere these days for obvious reasons — to study climate change. I don't know anybody working in this field who could make an estimate of the impact of thousands of tons of aluminium being dumped into the Earth's atmosphere. I don't know whether *you* do, but perhaps someone else here might have an idea of where that might be happening. That is such a high-profile problem, climate change, that adding that bit to it could have considerable impact.

Mr. Alexander. Certainly it's incredible — the different knock-on effects — they are everywhere you go. My personal view is everything in moderation. In November at the UK space conference on the effects of the orbiting satellites, it is a major UK research programme. I don't know where it is based. I would also say that the magnetosphere and the Earth's magnetic field will start to become of interest. I really do.

The President. A question on-line next.

Dr. Rowden. This question comes from Sanjeev Kalita: "Do we have space laws for exploring outer space such as colonization".

Mr. Alexander. I'm not a space lawyer. I don't know if the 1967 outer-space treaty covers colonization.

The President. Does anybody know?

A Fellow. It doesn't.

The President. Yet!

[*A City on Mars*, recently reviewed in these pages (**144**, 210), contains a very extensive discussion on the outer-space treaty and to what extent it covers present and planned activities in space. — Ed.]

Mr. Kevin McNulty. I'm just wondering with the satellites that were put up in the 60s and 70s — most of those can't do a controlled de-orbit, and if, in 10–20 years from now, the area around the Earth is packed with satellites, and if they all move out of the way to avoid a satellite coming through could that cause a Kessler effect?

Mr. Alexander. I don't know. Space is still very big and there is always the risk of collision. It takes only one collision to create thousands of pieces of space debris. In 2009 a Russian and an American satellite collided. China did a test with a satellite collision. There are about 40 000 pieces of debris being tracked at the moment, bigger than a mobile phone. Between 1 and 10 cm there are about a million pieces, and from 1 mm to 1 cm, about 128 million. It's just a matter of time and probability.

Dr. Quentin Stanley. I noticed that on the holding image as we came in here, there is a satellite on it. If you look at a Windows 11 build the first thing you get is an image of someone camping under the Milky Way and there are two satellites in it. Just to answer Kevin's question, Jonathan McDowell keeps a record of all the satellites, and you see these burns to move the objects out of satellite impacts and this goes on and on. You've done a brilliant job of highlighting these problems. Going back to Robert's presentation at Astrofest, this is something that concerned the RAS back in 1962 with radio astronomy. It's been going on for a long time and we need to put a bit more effort into it.

Professor Ofer Lahav. Given the situation at present with the amount of stuff that is out there, what is the forecast if nothing is done?

Mr. Alexander. I think it's an order of magnitude in the next ten years, by the end of the decade. Today there are about 10 000 satellites in space and there could be 100 000 in the next decade. There are currently licences for over a million.

The President. I'll just make a comment. For astronomical things that concern us a lot of mitigation can be done if the design of this craft is right and you have ways of shutting down a radio satellite with interference. A lot of work could be done on treaties if we could agree on the way the satellites are built, in reflectance, interference, and so on. That is one problem that can be dealt with. The debris problem is another matter but in a very serious way.

Professor Mike Cruise. Could I just suggest that people need to learn some lessons from what happened to the IPCC (Intergovernmental Panel on Climate Change)? What they found in their first ten years or so was that they had to be terribly careful about what they said, what graphs they produced, and so on. Not everybody who looks at your pictures or graphs will really understand what you are saying — some of the pictures, such as the re-use of the rubbish in space. I can see the front page of the *Sun* proclaiming "Boffins say a refuse park in space". The trouble is that you do not need a couple of hits like that to damage the case you are making. It's fantastic, but think carefully how pictures can be misconstrued by people, because the IPCC took a long time to learn how much damage was done by the public misunderstanding things they were saying.

Mr. Alexander. That's a fair point. There is a lot of aggressive lobbying but I think science communicators and policy makers felt they were walking on eggshells. We have an opportunity with space not to repeat that same behaviour and learn these lessons.

The President. I think that we are going to draw this to a close. Thank you, Max [applause]. Let me remind you that now, over in Burlington House, there is a drinks reception in the Council Room and you may like to continue some of these questions and comments over there. I give notice that the next open A&G Highlights meeting will be on Friday, March 8th.

THE STRUCTURE OF THE GALAXY AS DESCRIBED IN BRITISH PROFESSIONAL JOURNALS 1820–1920 PART 2: 1906–1920

By Steven Phillipps

Astrophysics Group, University of Bristol

Two previous articles considered early papers in British professional journals (primarily *Monthly Notices of the Royal Astronomical Society* and *The Observatory*) which turned out to be about external galaxies[1], and corresponding papers on the structure of our own Galaxy (up to 1905)[2]. Here we extend the latter until 1920 to cover papers up to the culmination of Harlow Shapley's series of papers[3,4] from Mount Wilson which