Solar Physics and Implications to Exotic Particles

MSc. Project Report
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Abstract

The study of Solar physics, Solar models, and various observations like helioseismology, neutrinos, etc. have allowed us to use the Sun as a laboratory for particle physics. They have allowed us to test the predictions of exotic particle physics and to go beyond the 'Standard Model'. Earlier in this project, in the first part, we discussed the construction of Solar models, helioseismology, the Solar abundance problem and its solutions and finally the implications of Solar physics on exotic particles. Here, in the second part, we continue to explore how we can constraint various properties through helioseismology. Then, we construct various potential research problems and lay out the related details to help us select the final topic to work on.

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Part I

Project stage - I

Chapter 1

Overview

The Physics of stars and the details of the stellar interior have always been a popular area of interest of people for ages. Especially the structure of the nearest star Sun has been explored the most. The dominant approach towards stellar physics has been to model the stellar structure using basic equations and compare the results with the observations. One of the tools which can be used to probe the interior is Helioseismology for the Sun or Asteroseismology for other stars. In the first stage of the project, we mainly focussed on developing our theoretical background on stellar physics and asteroseismology and their implications to exotic particles.

We discussed the related concepts such as we showed how to build the stellar models using the basic equations of physics and mentioned the input parameters required. We focussed mainly on the Standard Solar Model. Then we discussed the physics behind the stellar oscillations, the equations, their spherical approximations, and their properties and classification into p and g modes i.e. the acoustic and gravity modes respectively. We mentioned the basic observation tools for the p-modes and the importance of the frequency separation ratios as a diagnostic tool for probing the stellar core. Then we discussed some of the observation techniques and how helioseismic observations can be inverted to determine the solar interior details such as the Solar helium abundance, radius of the convection zone, and also the radial profile of the sound speed and density inside the Sun.

We also talked about how observations of the solar neutrinos, as well as the measure of the elemental abundances of the Solar interior using photospheric or meteoritic observations can be helpful and that the recent development of abundances has led to the revision of solar metallicity value to a lower value than the earlier one.

Then we discussed the consequences of the new abundances and how they conflict with the helioseismology i.e. the Solar abundance problem. We discussed some of the proposed solutions to the problem including some of the general and some exotic particle physics solutions. General solutions included solutions that suggested the changes in the basic input physics and parameters such as the opacity tables and abundances correction or inclusion of 3-D equations in the standard solar model, rotation, and other complex features in it. Solution based on accurate neutrino fluxes observations that can throw light upon the true abundances of some of the major elements such as C, N, and O. Some exotic particle physics solutions were also proposed in which they will contribute as the extra energy transport inside the Sun and hence affect the Solar model results and make them comparable to helioseismology.

We also focussed on the implications of stellar physics and discussed how helioseismology or asteroseismology has been used to constrain the exotic particle physics such as for determination of the mass or scattering cross-section or kinetic mixing parameter of dark matter or axions or hidden photons etc. and finally, how they can be used to probe the Dark matter content of the universe.

Part II

Project stage - II

Chapter 2

Introduction

The possibility of application of basic physics to distant objects like stars and comparison of results with the various observations has allowed us to use stars as laboratories to test the exotic particle physics. The Sun being the nearest star has been the most explored star and various observation techniques are being developed to know it further. Still there are various mysteries about the interior of the Sun that are still to be resolved. One such anomaly that we have talked about is the Solar abundance problem and we have explored some of the solutions to it. We have also seen how we can compare the helioseismic observations with the Solar model results to constraint various parameters and processes related to the new physics or exotic particles. This gives us confidence in our theories and allows us to build them better.

Here, in the second stage of the project we continue our exploration on the implications of Solar physics to the exotic particle physics. In chapter 3, we discuss how helioseismology can be inverted to infer the Solar core sound speed, temperature, Solar neutrino fluxes, and how we can constraint the axion emission process. Major part of the project includes the exploration and construction of a research problem to work on in future. In chapter 4, we first discuss the methodology (4.1) adopted to construct the questions and develop them and then to select some of the interesting and promising ones which can be our potential research problem. Then in the following sections we describe some of the selected questions and discuss the related theory, pros, opportunities and issues and the possible new thinking to solve the problem. First we list down some of the general problems related to the Solar physics (4.2, 4.3), then we focus on the effects of exotic particles on the Sun and related problems (4.5 onwards) and explore their consequences.

Chapter 3

Constraints on particle physics from Helioseismology

Helioseismology can be used to probe the Solar interior in detail allowing us to use the Sun as a laboratory to test new physics. Considering the role of exotic particles in the Solar interior contributes to the helioseismic and neutrino observations which can be further inverted to put constraints on some aspects of particle physics and Solar models. As in stage 1 of the project, here in this chapter, we continue to review and summarize some of the papers related to helioseismology and how it can be used to put constraints on the following parameters.

3.1 Solar core sound speed and temperature

Inversion of helioseismic data can provide us the sound speed u in the solar interior in terms of either the isothermal or adiabatic sound speeds using the equation of state. In particular, since observed p-modes do not propagate deep into the core where neutrino production takes place, we can determine the accuracy of sound speed in the core. Extensive analysis of the inversion method and the available data tells us that at the center, the sound speed is determined with a "1σ" accuracy of 1%.[1]

After knowing the sound speed, we can also determine the temperature in the Solar interior where the equation of state can be approximately given by the fully ionized classical perfect gas:

$$KT = \mu u \tag{3.1}$$

where μ is the mean molecular weight given as

$$\mu = \frac{m_{\rm p}}{(3/2X + 1/4Y + 1/2)} \tag{3.2}$$

where $m_{\rm p}$ is the proton mass and X, Y are Hydrogen and Helium abundances respectively. Hence, for a particular value of sound speed without any assumption on the chemical composition, we can get a helioseismic constraint on the Solar temperature as :

$$1/2u < KT/m_{\rm p} < 4/3u \tag{3.3}$$

3.2 Neutrino fluxes

Helioseismologic observations can be inverted to determine the sound speed and hence the density profile and the temperature and one can construct the Solar models using this data[2]. From this model, we can estimate the neutrino fluxes and then compare them with the current neutrino observations and hence determine stronger constraints on the neutrino fluxes than from the evolutionary SSM. From this method, helioseismology gives upper bound hep neutrino flux, and lower limit on the Beryllium neutrino flux, Gallium signal and Chlorine signal on Earth, etc.[1]

3.3 Solar Axion emission

Helioseismological sound-speed profiles severely constrain any possible deviations from the Standard Solar Model which allows us to derive new limits on anomalous energy losses, like due to primakoff emission of axions i.e. conversion of photons in the presence of coulomb fields of charged particles, $\gamma + Ze \rightarrow Ze + a$. We can construct the Solar models including energy losses due to axion emissions, with varying axion-photon coupling constant $g_{\mathrm{a}\gamma}$, which appears in the interaction Lagrangian. By comparison of these models with the neutrino fluxes and helioseismic observations, we can get a limit of $g_{\mathrm{a}\gamma} < 4.0 \times 10^{-10}\,\mathrm{GeV}^{-1}$. [2] [3]

Chapter 4

Constructing research questions

After building upon the theory and doing background research on Asteroseismology, Stellar models, neutrino observations, and exotic particles, we try to formulate a research problem to work on related to these topics. Here, in this chapter we describe the work done for the project. First, we talk about the methodology adopted to construct the research questions and to shortlist the most interesting ones. Then, we list down some of the interesting problems that were developed to a certain level and describe the necessary background details, pros, opportunities and, issues related to them and then try to address the issues as the new thinking part to some of the questions.

Note: This all was done as a group work.

4.1 Methodology

First of all, we tried to construct as many questions as possible related to the topic based on our background research in the first stage of the project. To converge on these questions, we first selected few interesting questions based on affirmative judgement and novelty. We then developed further on the selected ones following the acronym **POINT** as:

- **Pros**, positives, advantages, and strengths of the question.
- **Opportunities** related to the question i.e. the other related problems that can be possibly explained by it.
- **Issues** or challenges that we might face while trying to solve the problem.
- **New Thinking** i.e. the possible new direction to solve the problem or to address the issues mentioned.

To further shortlist the questions after developing them with **POINT**, we formulated evaluation criteria and score each question based on it and set a cutoff limit, and then selected the ones which clear the criteria and hence can be developed further. The evaluation is based on the following criteria with decreasing priority as:

1. Novelty
2. Audience interest
3. Availability of resources

4. Way forward
5. Tractability of solution
6. Success criteria
7. Topical
8. Seminal
9. Fill gap in literature

Further, we describe some of the pre-selected questions and the related details.

4.2 Future Observations to solve the Solar abundance problem

Can any future observations resolve the discrepancy between the helioseismology and the Standard Solar Models? Possibly, the detection of g-modes or mixed modes or any new p-modes can give us a better insight into the Solar interior. Then, how can we detect them and what might be the difficulties and how can they be overcome?

Background details

The p-mode Solar oscillations are trapped between the surface and the inner turning point and their amplitudes are significant only close to the surface for higher degree modes. They do not give significant information about the deep core of the Sun. Whereas, g-modes are trapped between the base of the convection zone and the core and can provide better details of the core but they are expected to have very small velocity amplitudes at the Solar surface, thereby making it difficult to detect them with usual doppler techniques.

There is a concentrated effort to detect g-modes. One possibility is through the detection of the gravitational wave spectrum which is predicted to be emitted by the Solar g-modes at very low frequency $\nu \leq 400\,\mu$Hz [4]. Currently, ASTROD and LISA(Laser Interferometer Space Antenna) are the two major efforts to detect the low frequency g-modes.

Pros, Opportunities

This research problem has a well motivated objective to observe the g-modes and the mixed modes. g-modes have most of their kinetic energy in the Solar core and also have smaller radial wavelengths in this region, which would provide a higher spatial resolution than the p-modes. If observed, they can provide much more precise inference on the structure and dynamics of the solar core than is possible with p-modes and hence, help us reduce the uncertainties in the Solar model right now. This can further have a bearing on the Solar abundance problem.

There is a possibility of detection of g-modes using changes in the large frequency separation of p-modes as they are perturbed by the g-modes. They can also be detected through the gravitational wave spectrum. The solution to this problem can help us identify other issues in the Solar models.

Also, for the mixed modes, the related theory and how they appear is very well developed, and since they are usually observed in stars at later stages of evolution like Red Giants, we might get some insight on the abundance problem with evolution. Their detection can give us some insight into the polytropic relations and therefore some results can be extrapolated to main sequence stars . Also, opacity and sound speed profiles would be different in the stars with observed mixed modes, and studying them might give us some insight on energy transport rates, and put constraints on oscillation frequency and therefore temperature gradients, etc., which might, in turn, put constraints on nuclear reactions.

Issues

If we try to solve this problem we might face some issues such as

- To detect g-modes how might we get the surface velocities to be large enough such that the consequent gravitational wave signature resides well above the detector noise?
- Or else how might we detect g modes solely through their signature in p-mode frequency shifts which is very small?
- If we propose a technique to detect them, how might we guarantee that it has enough sensitivity in a practical experiment and possibly better than existing/future sensitivities and is something novel?
- How might our technique be robust to misidentification of the effect from other possible backgrounds/sources within the sun?
- Mixed modes are rather ambiguous and difficult to resolve, then how might we construct the sound speed profiles from them or how might we extrapolate them to the main sequence stars to provide any insight?

New Thinking

Due to time constraints and our interest, we mainly worked on the issues related to the g-modes detection and developed some related new thinking.

The gravitational wave spectrum is emitted at very low frequencies, where the inherent seismic vibrations of the Earth renders the detectors on Earth impractical. So, maybe we can develop a way to differentiate between the earth's seismic vibrations and the ones through the gravitational wave spectrum.

According to the paper [4], observational results from Garcia et al (2007) gives an upper limit for the g-mode surface velocities to be about 0.3 mm/s at 100 µHz. The strain sensitivity curve for ASTROD is shifted towards lower frequencies, so, if ASTROD's orbit were modified to approach as close as 0.4 AU from the sun, then ASTROD will provide unambiguous detection of g-modes with frequencies between $100 - 300$ µHz.

To guarantee the sensitivity of the proposed technique, we can estimate the order of magnitude and precision of the g-mode observations possible and analyze and see if they make any difference to our current model, and how much precision can help us to get any difference.

Further development is expected on this question. Due to limited time, we could develop it only up till here.

4.3 Evolution of Solar abundance problem with stellar age

Can we study how the discrepancy of the Solar abundance problem evolves with the stellar age and if this discrepancy vanishes for a particular age? If yes, then how?

Pros, Opportunities

We notice that it is easy to evolve stellar models for different ages and compare them with observations from the Solar type stars at different stages of evolutions as the asteroseismic data for many stars in different stages of evolutions is available. This idea also seems to be relatively unexplored and hence seems interesting and novel.

The result of this problem can have a bearing on the inferred age of the Sun, and we can compare it with complementary tests of solar system age e.g. meteorite samples. The change in the discrepancy also might throw upon some light on the nature of nuclear reactions with age.

We can track such a change in disparity with respect to Dark Matter evaporation rates, settling rates, and other 'solutions' to the abundance problem. Studying such an evolution in stars in galaxies with different amounts of DM density can provide new insights into the effects of DM on the abundance problem.

But if the discrepancy in fact does not evolve with time, we may be able to rule out 'solutions' that change significantly with stellar age.

Issues

To try to solve this problem we might encounter some challenges such as:

- How might we establish consistent patterns across different stages of evolution and then extrapolate results from higher stages of evolution to the main sequence stars?
- How might we pinpoint the exact parameter that causes discrepancy at different stages?
- How might we argue if the existing inferences of the Solar age are wrong?
- How might we isolate the effect of age on the Solar abundances? How might we guarantee that the age is the most significant model parameter as opposed to things like initial metallicity etc?

New Thinking

We try to find out a possible direction to solve the issues related to the question. Some of them are as follows:

- To establish the patterns across stages of evolution we can compare the HR diagrams from existing globular cluster archives. To model such extensive clusters in MESA we may use archives of existing models. Then we may compare expected luminosity deviations etc.
- To find the exact parameter that causes discrepancy in abundances we can shortlist some parameters which we know suffer significant changes with age.
  - For instance, nuclear reactions can be modeled for evolution keeping in mind axions and DM interactions. We can tweak mixing length parameter etc. to try and fit our evolving models with observed HR diagrams.
  - We can cnsider change in the convection zone and its radius. This could affect settling rates, which might have an impact on the observed metallicity.
- To ensure age to be the most significant parameter in case the discrepancy really disappears, we will have to pinpoint the parameter that led to this change and see if its evolution with age is significant. We can try to rule out any other possibilities.

There are many other possible forward directions to this problem, and in the future we expect to develop them further to reach a conclusion.

4.4 Solar models and machine learning

Can we use our present Solar models to train machine learning algorithms to better extrapolate Solar interior properties given the photospheric and helioseismic data?

Pros, Opportunities

This problem is very interesting and novel. This shows us a new way to see the Solar metallicity problem. We can check the significance of Machine learning (ML) algorithms for the Sun-like systems, whether they are predicting anything different from well-known values or not.

We can also apply the ML algorithms in the Solar coronal heating problem. Maybe we can add the ML algorithms to get the inferences of the non-standard Solar Model. We can also apply the ML algorithms to other stars like White dwarfs and Neutron stars to get their evolution.

Issues

Machine learning algorithms for such systems are complex and we would need to first develop some skills in this field. Also,

- How might we test our predictions?
- How might we apply the algorithms to other systems than the Sun?

New Thinking

1. We can apply ML algorithms with helioseismology methods to check whether we can get anything new or different from what is suggested by helioseismology alone.
2. We can start the ML algorithms from the center of the Sun and run them beyond the Solar radius. In this way, we can check what is it going to tell about the Solar corona heating problem and abundance problem.

This problem requires much more background research and strong computational skills. Due to limited time, we could develop this problem only up to this level.

Exotic particles and dark matter

4.5 Exotic particles in the Sun and their consequences

What effects could exotic particles/Dark Matter produced in the Solar interior or coming from outside the Sun have on the structure of the Sun and how can they be calculated?

Background details

Exotic particles, if present, then can lead to energy loss or energy transport in the Solar interior or affect the nuclear reaction rates maybe as catalysts. They can also affect the opacities, sound speed profile, rotation profile, or diffusion rates of elements and magnetic fields inside the Sun. They may affect the planet formation or mass ejection or if they have a high interaction rate with metals then can affect the metallicity distribution as well.

Weakly-interacting DM from the Galactic halo can be captured when it passes through the Sun, and eventually settle into the Solar core. It can also scatter or annihilate inside and hence provide an additional means of conductive energy transport. DM capture, annihilation can result in energy loss/transport or change pressure and temperature or mass distribution and hence affect the helioseismic frequencies. Hence, the effects of DM (external particle stream) on the Sun are very similar to that of exotic particles produced within the Sun.

Here we try to address this problem in a broader view considering all kinds of effects. Later, we will focus on some specific effects which can have a stronger bearing on the Solar structure.

Pros, Opportunities

Exotic particles and their effect on the Solar structure is a very wide area of research. It has a lot of possible directions to work on. Possible detection of some of the exotic particles, like axions using helioscopes, can give us confidence in our assumptions. These exotic particles can be DM candidates as well, and so can help us solve many other mysteries.

The presence of exotic particles affects a lot of processes in the Sun which can completely change the current Solar model. These effects can explain the scenarios like Solar abundance problem, or Solar coronal heating as well. Using the constraints and the data on the exotic particles, we can account for their effects in the Sun in the Solar models within the allowed parameters and these results can be compared easily with the helioseismology. For the case of DM, their exists good models for capture rates and evaporation rates that can directly be used.

Their effects can be applied to other stars as well and be verified. They can also contribute to several stages of stars (like core-collapse, mass ejection, and overall stellar evolution). We could also get new effects of exotic particles, which have not been explored yet.

Issues

To solve this problem we might have to first find a solution to some of the issues such as :

- To consider the effects of exotic particles in the Sun, how might we first find out strong evidence for their existence?
- Then, to account for their role in the Solar interior, how might we develop a model with known exotic particle properties to check its effects on the Solar interior?
- After accounting for their effects in the Solar model, how might we estimate if they would have a significant contribution or not? and then determine the parameters and stronger constraints on exotic particles?
- How will we be sure that any new effect is coming from the exotic particles, and not from any other mechanisms of known physics?
- Also, how might we detect these effects or how might we observe any such deviations if they are almost negligible?

New Thinking

- Detection of axions through primakoff conversion using helioscopes can provide us some evidence for their existence in the Sun. Also, if exotic particles alter nuclear reactions, then neutrino emitted in such a reaction is detected then maybe can tell us about exotic particles and their properties.
- If the dark matter particles are present inside the Sun then they can extend the results of many works that have considered only the presence of protons and electrons inside the Sun. For such models, we can get slightly or completely different results and simulations. So, we may get different ranges in energies of reflected dark matter particles.
- Then to develop the models, we need to first build up theories on how do each effect can be accounted for in it and then evolve them till the Solar age, and then we may compare the results with the helioseismology to get some constraints on the parameters used.
- Assuming the presence of dark matter particles inside the Sun, We can get new limits on the dark matter-proton cross-section, dark-matter electron cross-section. If we simulate the stellar evolution assuming that some dark matter reactions are going on then we can put some constraints on dark matter particles.
- Also, using asteroseismic data of stars present in dark matter dense areas, and constructing stellar models for them, and then comparing them, can provide us better and stronger constraints on the parameters involved.
- To estimate the significance of the effects, we can use the constraints of several parameters and compute the effects of exotic particles in the solar interior through various methods such as energy transport, effect on magnetic fields, opacity, etc and can estimate maximum and minimum deviation possible and if it's significant enough.
- To be able to observe these negligible deviations, we need to build experiments such that they have very high resolution and precision to detect these negligible changes as well. Maybe we can try to think about possible methods to do this.

- Some major scenarios for the effect of dark matter from outside the Sun are (a) Dark matter halo particles, (b) Lumps of Dark matter, (c) Some proposed models like the "Axion quark nugget model ." For these selective cases, we can expect different kinds of effects from outside the Sun and there is already a lot of work being done in these areas.

4.6 Effects of exotic particles on Diffusion rates

What effect the exotic particles will have on the diffusion rates and how can they be measured? How will the change in diffusion rates then affect the surface, or core abundances, opacity profile, and evaporation rates?

Background details

In the conditions of the Solar interior, chemical elements suffer gravitational settling or diffusion which is the slow segregation process due to the effect of the gravitational and electric field which are there due to the gradients of pressure and temperature in the Sun. It affects elements differently based on their nuclear charge to mass ratio $Z_{\rm nuc}/A_{\rm nuc}$. But for the Sun, diffusion rates are approximately the same for all metals and helium.

Diffusive drainage of the heavier elements from the convection zone reduces their abundances relative to hydrogen in the Sun's atmosphere. This reduction is inversely proportional the depth of the Convective zone. Due to this, SSM calculations show that the diffusion leads to the $10 - 12\%$ decrease of the Solar surface abundances with respect to the primordial values.[5]

Pros, Opportunities

The question of the effect of new particles on diffusion rates or settling is a novel idea and has many possible sub-questions which can be worked upon. Changed diffusion rates can be accounted for in the Solar models and the results can be compared with the helioseismic predictions, hence, it has testable predictions.

This problem can also be connected to DM and maybe it can have a complementary effect on current ways of thinking about direct detection of dark matter in the Sun.

If there is an increase in the diffusion rates then it will lead to higher helium and heavy element abundance in the radiative interior, thereby increasing opacities and thus bringing the structure of the radiative interior closer to that in the Sun. Diffusion rates affect the equation of state as well and in stars of very great age, diffusion effects may become important in the atmospheric layers which can be subjected to spectroscopic analysis. It may also affect the neutrino oscillations in the Sun. Hence, this problem can be related to the Solar abundance problem and coronal heating problem.

Issues

- To start solving this problem we first need to know how might new particles affect the settling rate? Do they only change the gravity by altering the structure of the Sun? Or do they create new forces in the Sun?

- How might we ensure that such an effect preferentially affects metals?

- How might we reconcile such new particles with the existing constraints?

- How might we connect such particles to interesting anomalies motivated by particle physics theories?

New Thinking

New particles can affect the Sun through processes like scattering, decay, or gravitational clumping. They might contribute to a background field and change the gravity or they can create new forces in the Sun due to long-range interactions, for eg., asymmetric dark matter with long-range interaction maybe could pull in heavy elements.

After this, in order to have an effect on the settling rates, we would need to understand the diffusion in a background gravitational field of the Sun in more detail. It seems that to have an effect on the time scale of diffusion we need to change either of the

- temperature
- mass of the drifting nucleus
- gravitational field (but it seems that it may affect all the particles equally)
- cross sections with targets or viscosity
- size of the particle

Change in viscosity seems promising if we consider the scattering with some exotic particles in the Sun. But for this, we need to confirm that for a gas increase in the cross-section would lead to a decrease in viscosity. We will also require preferential scattering of heavy metals.

Further thinking is required to fully solve this issue and to come to a conclusion. We have explored only up to this level in the available time.

4.7 Effects of exotic particles on the Solar rotation profile

Can new particles alter the rotation profile of the Sun or the moment of inertia of the Sun? Can that contribute to the rotational splitting in helioseismology?

Background details

The Sun rotates about an axis differentially i.e. at different rates at different latitudes. This differential profile extends to the Solar interior and at the tachocline where the rotation abruptly changes to solid-body rotation in the Solar radiation zone. The evidence of Solar rotation in the interior can be seen through the rotational splitting of p-mode frequencies as the rotation lift the degeneracy between the modes of the same l and different m.

Pros, Opportunities

This question of exotic particles' effects on the rotation profile of the Sun is a relatively novel idea and has many testable predictions. Exotic particles and then change in rotation profile can alter the structure of the Sun which can be verified with the helioseismic and neutrino observations. This has possible complementary tests in direct detection experiments. It could also allow for detailed studies using line splitting in helioseismology.

A solution to this problem could give us an explanation for the Solar abundance problem, Solar dynamo mechanism and magnetic fields.

Issues

To know further implications, we need to know

- How might new particles alter the rotation profile of the Sun?
- How might we reconcile these effects with the known structure of the Sun or the constraints from helioseismological line splitting?
- How might we reconcile any other effects with constraints from particle physics?

New Thinking

Rotation profile might be affected by new particles through their:

- **Accretion or capture in the Sun :**
  - This could change the moment of inertia of the Sun. This perhaps would be angular momentum supported to prevent their settling as the capture of particles require multiple collisions which could alter the angular momentum and lead to condensation in the core.
  - It could probably affect g-modes only.

  But then, we need to know what fraction of the Sun can be made up of captured DM.

  This direction can have interesting connections to WIMPs (Weakly interacting Massive particles) or IceCube searches.

- **Production in the Sun at different distances :**
  - Spherically symmetric production

    This could again alter the moment of inertia, and we need to capture the particles, and need to prevent their settling.
  - Asymmetric production
    * This could perhaps happen due to existing rotational asymmetry of the spin axis. This could give feedback to rotations which might alter the spinning rate.
    * It is possible that for every compression cycle temperature, T and pressure, P goes up in some region and hence changing the production rate of new particles. But, for this we would need high T^n dependence, perhaps a high dimensional operator.

    Could there be production due to magnetic fields or due to rotating plasma effects?

- **Effect on magnetic fields :**

  The new particles could change the magnetic fields (e.g. through axions) and this could maybe lead to alternative plasma confinement that varies with magnetic field.

4.8 Effects of exotic particles on the nuclear reactions

Can dark matter or other exotic particles act as a part of nuclear reactions and hence alter the metallicity? Can they affect nuclear reaction rates acting as catalysts? Could a change in the nuclear reaction rate affect the rate of gravitational settling?

Background details

The energy sources of the Sun are the nuclear fusion reactions mainly the 'proton-proton chain' and the 'Carbon-Nitrogen-Oxygen (CNO) cycle'. But there are various other nuclear reactions that take place in the Solar interior. Such as the fusion and fission of heavier elements i.e. the thermonuclear reactions like triple alpha reactions, alpha reactions, Carbon burning, Oxygen burning, Silicon burning, etc. When the photon energy becomes high enough to destroy certain nuclei then the photonuclear reactions take place. The production of elements heavier than Iron requires an input of energy, and therefore such elements cannot be produced by thermonuclear reactions and are almost exclusively produced by neutron capture during the final violent stages of stellar evolution.

The rates of these nuclear reactions depend on the physical environment at the site. Hence, if there is any change in the physical conditions of the Solar interior due to the presence of the exotic particles or their emission, then the reaction rates too will be affected which will further change the Solar model predictions which can give us a lot of new information.

Pros, Opportunities

The effect of exotic particles on nuclear reactions seems to be a relatively unexplored area, therefore holds a novelty factor. This problem is quite well-formulated and is straightforward to be addressed. So, we have many ideas to work on this, like the exotic particles can act as catalysts or contribute to a background field that might affect the nuclear interactions. This could also be related to the Solar abundance problem.

This problem has many testable predictions as it can

- affect theoretically predicted neutrino rates
- give different yields i.e. alter spectral lines
- affect the interior structure and yield different sound speed profiles
- affect the convection zone and hence alter helioseismic measurements
- maybe affect the overall HR diagram e.g. slowing down stellar evolution for other stars as well
- affect later stages of stellar evolution and can be seen in supergiants, white dwarfs

Issues

We first need to address these issues :

- What could be the possible mechanisms through which exotic particles could affect the nuclear reactions?
- How might we know if there would be a significant effect and if the mechanisms like catalysis and background field contribution would work?
- How might we study the effect on all reaction rates to get accurate predictions as lots of pre-computation would be required?

New Thinking

Some possible mechanisms which can bring changes in the nuclear reaction rates are:

- **Potential paths** : the presence of exotic particles inside the Sun can change the resultant interaction potential among the interacting particles.
- **Change in core conditions** : there can be changes in the temperature, pressure, or density profile in the core due to the presence of the new particles and that modify the nuclear reaction rates.
- **Weak interaction :** One of the main nuclear reactions inside the Sun is the $p-p$ reaction ($p+p \rightarrow^2_1 D + e^+ + \nu_e$) which undergoes weak interaction, so, if the exotic particles are also taking place in the weak interaction then they will also change the rate of this reaction.
- **EM repulsion barrier :** for the interaction of two charged particles of the same sign, they have to overcome the electromagnetic repulsion between them, so the exotic particles can also change this electromagnetic repulsion which will lead to the modified reaction rates.

  But how might new particles alter the electromagnetic barrier? Here are some of the possibilities:

  - **Bound states $(p+X)$** : If first the protons (p) form bound states with dark matter particles (X) and then interact, this would change the electromagnetic barrier.
  - **Bound states $(X+X)$** : Another possibility could be that the dark matter particles form a bound state $(X+X)$ that supports the interaction of two protons. Hence, it can work as a catalyst that can alter the nuclear reaction rate of the two protons.
  - **Background field (X)** : The new particles could also act as a background field assisting the nuclear reactions, by lowering the repulsion barrier.

4.9 Effects of exotic particles on the opacity profile

How do different types of DM interactions affect the opacity profile?

Pros, Opportunities

The area of dark matter interaction with matter is explored enough and we already have a bunch of dark matter models to work with. The axion-photon and axion-electron coupling are also well studied. We also have some limits on the axion-electron coupling so the main process of absorption inside the stellar interior which is “bound-free” absorption can also change the opacity profile.

As stars import their internal heat primarily by radiation so the coupling of axions with photons will be a key input. We can use the known coupling to test the changes in the opacity table. Any changes in opacity profile caused by DM interaction can lead us to whether a changed opacity profile can solve the Solar abundance problem or not.

Issues

- How to be sure that any change in opacity profile is caused by dark matter interaction?
- How might we gather confidence in our models since we have not yet detected any kind of dark matter interaction with matter?
- Or, how might we detect any kind of interaction between DM and matter?

New Thinking

Different types of interactions can change the radiation profile of the Sun and hence the equation of state, which in result can change the opacity profile.

If the dark matter interaction is temperature dependent then it can also affect the opacity. As opacity is a function of temperature and density, so any kind of dark matter density profile can affect the opacity profile and maybe increase the opacity.

4.10 Exotic particles and Magnetic fields

How do exotic particles/DM get influenced by magnetic fields within the Solar interior? How do magnetic fields affect the gravitational settling rates? Can we infer this from surface magnetic phenomena?

Background details

The Solar magnetic field is generated by the motion of the conductive plasma inside the Sun. This motion is created through convection and creates a global dipolar field. As the Sun undergoes differential rotation, the magnetism is wound into a toroidal field of "flux ropes" that become wrapped around the Sun. Due to the Lorentz force, charged particles are forced to spiral around magnetic field lines and cannot cross them except by collisions hence the particles are trapped. In regions of open field lines, however, particles can actually follow the lines out away from the Sun. Magnetic fields are responsible for Solar winds, sunspots, solar flares, etc.

Pros, Opportunities

The problem of the effects of magnetic fields on exotic particles seems to be novel and has many testable predictions. Magnetic fields affect the sunspot activity, helioseismic observations, etc., through which we can get good models for the surface magnetic activity and would help us deviate from the static helioseismic models.

The effect of magnetic fields on exotic particles/DM can affect energy transport rates or interaction rates of particles. This will then have significant effects on computational models and will help us put new bounds on the coupling constants. We can also get estimates on the accumulation of charged particles at the base of the convection zone.

It can help us study the interaction between 'background' fields and the magnetic field. This will also through insight on the effect of DM on nuclear reactions.

Issues

Some of the challenges we need to overcome to come to a solution to the problem are :

- How might we ensure that rapidly changing magnetic fields will have observable effects on DM transport rates, etc.
- How might we computationally model such fast changing fields?
- How might we relate surface magnetic fields to conditions in the interior?

New Thinking

In regions of strong magnetic fields, there is absorption of p-modes, hence, through observed p-modes we can infer the changing magnetic fields and other conditions.[6]

Also, in the detection of axions, magnetic field is a key parameter as with a high magnetic field we have a large probability to detect the photons coming from the exotic particle conversion inside.

In the available time, we could develop this problem only up till here. Further work is expected after this.

4.11 Energy transport solution to the Solar abundance problem

What is the energy transport solution to the problem and how is it calculated?

What all possibilities (which particles) are there, what are the properties of such particles and how should they contribute to energy transport or interact in the Solar interior?

What are the sources of such exotic particles? What are the mechanisms for their generation, capture, emission, annihilation, etc.?

Background details

All of the energy inside the Sun is created through nuclear fusion reactions in the hot, dense, high pressure core. This energy is transported to the surface of the Sun mainly through 2 mechanisms i.e. radiation and convection. In radiation diffusion, energy is transported from hot regions to colder regions through photons through their absorption and re-emission in random directions on their encounter with matter . Here, the opacity of matter plays an important role. In convection, hot, buoyant mass elements carry excess energy outwards and the cooler elements fall inwards. In the Sun, energy is transported by convection in the outer regions of the Sun (the outer 30 percent, or so)and by radiative diffusion in the inner regions of the Sun (the inner 70 percent).

Pros, Opportunities

This problem is well defined and has many possible sub-questions, and many solutions exist and seem to be promising. Various details can be predicted from a helioseismic reconstruction of Solar properties and comparison with theoretical predictions and verified by putting back into the Solar models.

These possibilities with helioseismology can give us a clearer picture of the inner Sun than the present. The solution can be applied to many other stars and results can be compared with their asteroseismic determinations. All these possibilities can explore the area of star cooling (White dwarf cooling, Neutron star cooling).

Other inferences from the solution can be :

- Mechanisms and particles responsible for energy transport can be better constrained through the Solar data.
- Can give us an insight into the interactions of exotic particles with matter and their creation/annihilation/escapement mechanisms etc.
- Can tell us about the other constituents of the universe other than known matter and resolve mysteries around dark matter etc.
- Can provide a target for lab searches for weakly interacting light particles.

Issues

Some of the issues that we need to address to get to a solution are :

- How might we propose an alternative mechanism for energy transport with new particles or change the type of particle interaction? e.g. mechanisms based on settling rather than being radiation driven, or convection driven, or interaction rather than free streaming driven?
- How might we gather more evidence on these solutions which are based on assumptions?
- How might we observe any of these possibilities due to energy transport?
- How to distinguish our possibilities from the earlier proposed ones and propose something novel?
- How might we ensure that our new effect does not alter other Solar observables significantly?
- How to ensure if our new particle is safe from existing bounds from stellar physics /other sources?

New Thinking

It has been suggested that the solar abundance problem can be solved by a localized loss of energy near the radiative zone boundary and a gain of approximately the same amount of energy inside the solar core[7]. So, we can find a mechanism to achieve this and associate it with different particles like hidden photons or axions, etc. and compare the result with helioseismology, neutrino observations, etc.

We can apply the energy transport solution to other stars and compare the results and even get stronger constraints on various parameters.

Detection of exotic particles can provide information about their interactions in the Solar interior and hence tell us about their effect on energy transport.

The results can be used to explain why we have more stars on the Horizontal branch in HR diagram depending upon the energy loss at several stages. We can also get an explanation for why we have less number of observed solar neutrinos.

4.12 Desirable properties of Exotic particles

What are the desirable properties of new exotic particles that can solve the Solar abundance problem?

Pros, Opportunities

The properties of the exotic particles (if identified) can lead to the explanation of many problems in particle physics and Astro-particle physics and in Solar physics such as the Solar abundance problem, Solar Corona heating problem, etc. These properties can contribute to the vast search of dark matter particles.

This problem can help us explore the area of physics beyond the standard model. It can push some favored dark matter particle models as well.

These properties can be determined from various constraints that we get from different stellar models and asteroseismic observations. Hence, the solution to this problem has testable predictions.

Issues

Some of the challenges we would face while finding the solution to the problem are:

- How might we detect or observe these properties by our detectors and telescopes?
- How to explain these properties with known particle physics. (the Standard Model of particle physics)

New Thinking

Maybe, these exotic particles interact with heavy elements/metals (Z) inside the core and motivate them to decay into lighter particles. This way, they would affect the energy production mechanisms in the core and would affect the Solar interior properties. These effects can be detected through helioseismology.

Maybe, these exotic particles are creating a shield around heavy elements so altering their observations.

4.13 Neutrino Observations

What are the different background components in neutrino measurements and how to distinguish them from the required neutrino flux? What is the sensitivity of different neutrino detectors? How much accuracy in neutrino measurement is sufficient to solve the Solar abundance problem? How to infer the metallicity from the neutrino flux?

Background details

In the Sun, electron neutrinos are produced as a product of the nuclear fusion reactions. The main contributions are from the proton-proton chain and CNO cycle. For the proton-proton chain, there are five neutrino components (pp, ^7Be, ^8B, pep and hep) each with a different spectrum, while for the CNO cycle, there are three (^{13}N,^{15}O and ^{17}F), and we refer to the sum of the latter as the CNO neutrinos. Each reaction has its own spectrum of neutrino energies. The number of neutrinos and their energy spectrum can be predicted by the standard solar model with high precision.

These neutrinos can be detected on the Earth through various observatories. Different neutrino detectors are sensitive to different neutrino energy ranges and can detect the corresponding neutrinos only. In the detectors, at particular energy there are some background neutrino components as well which we need to remove from our observations to get accurate predictions of Solar neutrinos.

Pros, Opportunities

Observation of neutrinos and inferences of Solar metallicity from it is a popular area of research and many experimental techniques exist which after further advancements can answer the questions precisely.

Solving this problem, we can get precise results for neutrino flux measurements from the Sun and tell accurate abundances of metals in the core and this can help lift degeneracy between opacity and metallicity which will then have a strong bearing on the Solar abundance problem.

Helioseismic inversion can help us estimate the accuracies and time required in detection to estimate abundances up to the required level of confidence, the improvement required in the experimental detection techniques. Further analysis of this problem can suggest strategies to improve extraction of metal abundance from neutrino fluxes, and new pathways of neutrino production in the Sun. It can have an effect on neutrino oscillation parameters and can suggest new catalytic effects of metals. Also, precise measurements can throw light upon exotic particle interactions with matter.

Issues

Some of the issues we need to resolve to get a solution to the above questions are :

- How might we more directly relate neutrino fluxes to the metal abundances?
- How might we know all sources of neutrinos to account for exact background components?
- How might we make experimental advancements to solve the issue properly rather than using estimates?
- How might we propose something novel that has yet to be tested?
- How might we propose an analysis which improves upon existing studies?

New Thinking

If we know all the nuclear reactions going on in the solar interior and the reaction rates and flux relations, we can relate the neutrino fluxes and the metal abundances.

Different Solar models and experimental observations can tell us about the reactions and hence sources of neutrinos, but there can also be some neutrinos from reactions due to exotic particles for which we need stronger theory and evidence to account for.

We can find out the limits up to which different experiments can detect neutrino fluxes and how much improvement is possible in the next few years, and hence estimate the fluxes and their effects on the solar model.

We can invert helioseismic data to estimate neutrino fluxes and compare them with the experiments and observations and try to build upon theory to explain the discrepancies or estimate improvement in experiments required.

This problem is much more experimental details related, hence we need to explore more on the background to come to a proper solution. Further development of the solution is expected later on in the project.

4.14 Change in metallicity due to accretion of matter

Can metallicity change through accretion? Possibly with new particle physics?

Can a clump of dark matter passing through the Sun knock out or pick up metals as it passes through?

Pros, Opportunities

The accretion of metals or dark matter to alter the metallicity is an interesting idea, and there are many possible ideas to try out. It's a novel idea to show how accretion could be affected by DM or exotic particle physics. This problem can be related to the Solar abundance problem as well.

The solution to this is complementary to direct detection tests. It is also relevant for Primordial Black Holes (PBH) clump dark matter or axion mini clusters and could also probe the PBH DM low mass window.

Issues

Some of the questions we need to answer to get a solution to our problem are:

- How might we get an effect in the first place?
- How might we ensure that an effect due to exotic particles is more dominant than the natural accretion of metals?
- How do we ensure that such an effect is not ruled out by other searches?

New Thinking

Young stars interact and accrete material from their proto-planetary disk. The planet formation process is likely to alter the average composition of the proto-planetary disk. Since planets in the Solar system are metal-rich compared to the Sun, so, if a part of the partially metal depleted disk is accreted onto the young Sun, the solar interior will have a higher metal content than the envelope [5]. This can have an explanation for the lower metallicity of the present Sun.

We can construct models based on this process and can put constraints on various parameters and find a solution to the problem. One can fine-tune the mass and chemical composition of the accreted material so that the convection zone radius is close to the seismic value but, at the expense of Helium abundance. This gives too little Helium abundance, and we need to add some Helium to be accreted on the surface over the lifetime of the Sun, after the formation of the metal rich interior of the early Sun. So, our goal now in this problem is to accrete helium.

Suppose we had many encounters with DM clumps over the history of the Sun. These encounters could deposit metals/Helium onto the Sun either directly or through some interaction - e.g. quark nuggets etc.

- For this to work we need many encounters over the history of the Sun
  - Number of encounters = age of the Sun/time scale of encounter
- While the encounter rate of clumps depends on mass, the total mass that encounters the Sun does not. So,
  - Total mass that encounters the sun = number of encounters * mass of the clump
- Assuming we need to accrete Helium only onto the outer surface of the Sun i.e. from $R_{\rm cz} = 0.7R_{\odot}$ to the surface and we need to change Helium abundance by i.e. $\triangle Y = 0.02$, we would need an extra helium mass of the order of
  - $\Delta M_{\rm He} =$ volume fraction of outer region $* \Delta Y * M_{\odot}$
  - we can see that the total dark matter mass encountered by the Sun over its lifetime is many orders of magnitude smaller than this!
- We need to figure out a way to increase the mass accretion rate for any given DM clump mass
- Or we need a way for 1 kg of DM to convert Solar material into required amount of Helium
- Or we need to review if our calculation for the mass of Helium needed is correct, based on references related to the metal accretion solutions to the Solar abundance problem

4.15 Equation of state of Solar models

What are the equations of state used to construct solar models? How are polytropic models used in steady state equations? Can a change in polytropic parameters help us solve the Solar abundance problem?

Pros, Opportunities

Environment conditions in the Sun are not clearly known hence, the equation of state used in modeling the Sun might not be accurate. We need to modify the equation to correctly satisfy the properties of the Solar interior.

Lots of models for the determination of the equation of state are available and we can input them into Solar models and see the results and can compare them with the observations, hence, this problem has testable predictions. Many other stars can be modeled and tested to give confidence in a particular equation of state.

Modified equation of state can alter the Solar models and can give us improved results of abundances and hence, can be related to the Solar abundance problem.

Issues

Some of the issues related to the problem that we need to solve are:

- How might we model a change in the equation of state (EOS)?
- How might we account for the changes in opacity and other quantities by changing the EOS?
- How might we estimate if the changes are significant enough to alter our solar models?
- How would we ensure that our new particle/interaction altering the equation of state is allowed by the experimental searches?

New Thinking

Some of the possible directions to work on this problem are:

- If there are any exotic particles inside the Sun then, they are going to affect the EOS and hence the polytropic parameter which would bring a change in the opacity profile. This could then help us resolve the discrepancy in the abundances.
- If the EOS for Solar plasma is different from ideal gas (like, Wander Wall gas) then we will have a different EOS that may follow the same path as above to resolve the ambiguity.
- Since pressure, density, temperature profile inside the Sun is different from the core to the surface so we can have different EOS in different layers so, we can model the Sun such that there is layer by layer evolution. This could throw some light upon the Solar abundance problem.
- The number density distribution profile for particles in EOS expressions is momentum dependent, which might get affected by interaction with exotic particles etc.

4.16 Axion detections and Helioscopes

How do helioscopes work or detect axion signals? How much information can they provide?

Background details

Axion helioscopes search for thermal flux of axions and axion-like particles expected to be emitted by the Sun. They detect axions via inverse Primakoff conversion in strong laboratory magnets pointed at the Sun. When axions pass through the applied field, they convert to high energy photons. The probability of conversion of axions to photons and their detection depends on the Solar axion flux, magnetic field applied and the axion-photon coupling constant $g_{\mathrm{a}\gamma}$.

Pros, Opportunities

Detection of axions is a popular area in experimental research. Axions interact with photons and this can be used to detect axion signals at Earth. Many experiments are being performed and we can build theory to interpret the observations. The detection can prove the existence of axions and hence our proposed idea with axions too. This could also help us to measure or constrain the Solar magnetic field.

The existence of axions inside the Sun can make significant changes in opacity profile and can lead to the solution of the Solar abundance problem. The answer to our problem throws light upon the axion content of the Sun's core which can participate in the energy flow mechanism and help us improve the Solar models.

Axions are also candidates to solve the Dark Matter (DM) problem. Like WIMPs, axions are especially interesting to solve the DM mystery. Together helioscopes, haloscopes, and laboratory searches can provide a complementary approach to close in on axions and other dark matter candidates.

Issues

Some of the challenges that we need to overcome to get a solution to the problem are:

- The probability of axion detection depends on the magnetic field, which cannot be increased arbitrarily so, how might we increase the probability of detection?
- Due to a finite limit of helioscopes, how might we make detections for a larger range of axion parameter space?
- How might we make the detection of axions and its interpretation model independent?

New Thinking

The detection is going to take place by the conversion of axions into photons in the presence of the Magnetic field (Primakoff conversion). So, the number of detected photons per unit of time can give us information about the axions coming out from the surface of the Sun per unit of time. Hence this can explore the ambiance of the Solar interior.

The detection of axions can lead to new solutions to the Solar corona heating problem. The energy transport mechanism solutions due to axions can help us solve the Solar abundance problem as well.

We can test the limits of the helioscopes to check if there is a detection possibility of any other kind of particle by helioscopes that are taking part in energy transportation.

This problem needs more attention to come to a proper solution, but due to limited time, we could develop it only up till here.

Chapter 5

Conclusion and future work

We have seen that there are various questions related to Solar physics and particle physics that can be addressed as a research problem. Each problem is itself too vast and interesting and can be a potential research topic. However, we had to shortlist some of them which were the most exciting for us, to be able to decide upon one research problem that we would work on amongst them.

We have listed here some of the selected questions from the big bank of questions that we developed at the first stage. These questions were developed to provide us some insight into the details and opportunities they hold for us and how might we work on them. After this, we evaluated each problem based on our criteria listed earlier and further shortlisted some of them. The final shortlisted ones from those mentioned above are :

1. Future Observations to solve the Solar abundance problem 4.2
2. Evolution of Solar abundance problem with stellar age 4.3
3. Exotic particles in the Sun and its consequences 4.5
4. Effects of new particles on Diffusion rates 4.6
5. Energy transport solution to the Solar abundance problem 4.11

Due to limited availability of time, we could only work on this project up to this level i.e. shortlisting of the potential research problems. We are still working on developing new ideas to solve each question and address the issues. In the future, we plan to do some estimations of the results that the new ideas could provide us. These estimations would further allow us to compare and then select our final research problem which we can properly work on.

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Appendix A

Plagiarism check report

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