# Crochet The Universe

# Contents

# Introduction

This booklet is full of patterns for various space-y physics concepts for you to crochet. The idea behind the patterns is for higher level physics concepts such as black holes to be made into easily visualisable and holdable models that can be used for classroom demonstrations, or they can be made just for fun!

The models are laid out in this booklet in order of "complicatedness", with the last patterns requiring more background physics to understand well. That being said, there will be lots of information to help you understand what the pattern is and to get you up to speed!

## Yarn & Hooks

Each model is small enough to be held in your hand using dk (8ply) weight yarn, with the exception of the 3D Hertzsprung-Russell Diagram. You are welcome to use any weight of yarn and any hook that makes your stitches nice and tight, as **there is no need to gauge swatch**. Expect a larger model when using aran and chunky yarn, and a smaller one when using sport/fingering etc.


The models in this book used dk weight acrylic yarn (Stylecraft Special dk) with a 4 mm (US G) hook. Once again, use whatever size and hook you please, none of these are to scale anyways!

Almost all types of yarn are suitable for these models. Stylecraft special dk was chosen as it is usually the most affordable option, but if you would like to veer on the cost-saving side, I would recommend using fewer colours and that you look into yarn that comes in 50g balls as some of the colours were not used much. **This could also be the perfect time to stash-bust!**

The most used colours chosen for these projects were black, white, yellow, orange and red. For the Hertzsprung-Russell Diagram purple, light and mid blue were also needed. The cosmological geometry models used a ball  of stash yarn, but for these models  any colour yarn will work!

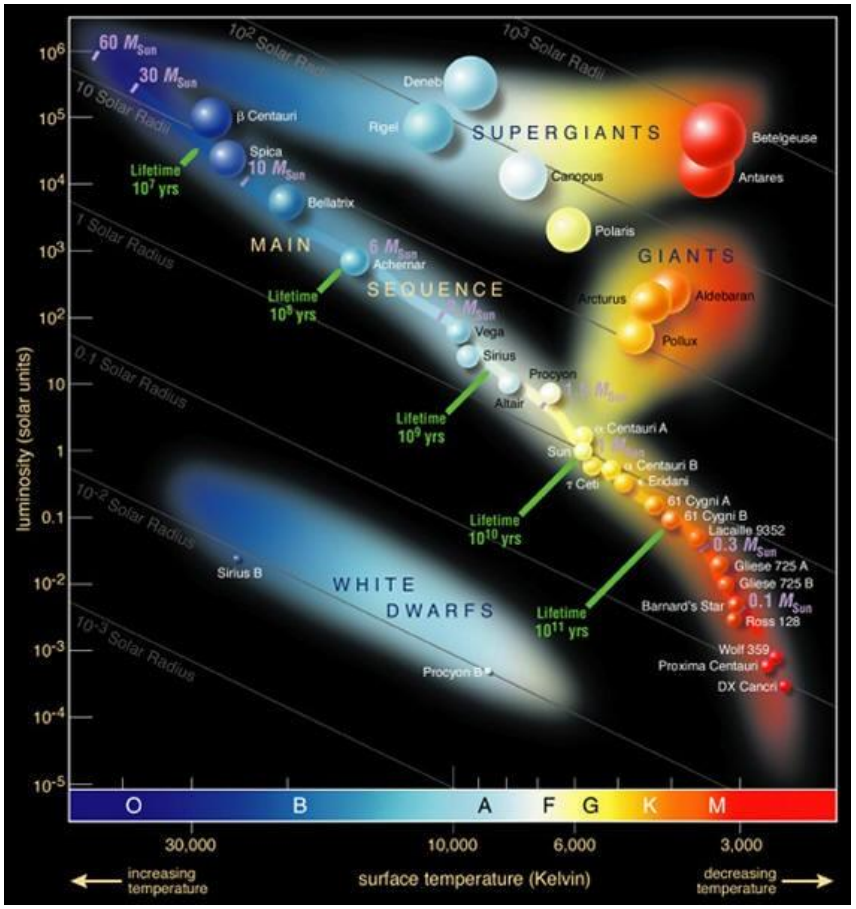
## Abbreviations

All patterns are in **US terms** and with standard crochet abbreviations. A list will be provided below as a reminder:

**sc** single crochet
**dc** double crochet
**hdc** half-double crochet
**sl-st** slip-stitch
**ch** chain
**hdc2tog** half-double crochet 2 together
**sc2tog** single crochet 2 together

## 3D Hertzsprung-Russell Diagram

### What is a HR Diagram?




HR diagrams (Hertzsprung-Rusell) are incredibly useful diagrams that plot a star's intensity/luminosity against its temperature. From these graphs, one can find the size of a star, and also see the life story of different kinds of stars.

On the left is an example HR diagram, with accurate colouring. The amazing thing about HR diagrams is that only 2 variables (luminosity & temperature) are plotted, but multiple other variables can be pulled out of it, such as colour.

For example:

- ★ Stars are almost perfect black bodies (they absorb & emit all incident light) so their colour can be very easily determined from temperature. Just divide 0.00289 by their surface temperature in Kelvin, and you get the colour they are as a wavelength!

- ★ The long diagonal strip contains the most stars, suggesting it's a phase in the star's life where stars stay the longest. This is the main sequence, and it shows that hotter bluer stars are brighter (more luminous) and hence must go through fuel quicker, while cooler redder stars are dimmer. The other stars that aren't on the diagonal line must therefore be in different phases of its life (we know this is the end of its life, as either a red giant, supergiant, or white dwarf).

The HR diagram is a great way to compare stars with each other and make connections between different areas of stellar astrophysics (e.g. luminosity and size). Due to the nature of it being a graph, it can be used for a range of education levels.

One of the main limitations is that the above diagram doesn't have the stars to scale with each other, however, and I think it could really benefit from size comparison. This would be especially beneficial for teaching people who aren't used to log/exponential scales as stars' sizes increase exponentially.
However, there are also limitations with the crochet model:

- This pattern is thus for a HR diagram that includes star size. It can't include the supergiant/hypergiant stage due to the sheer size.
- While the crocheter is free to add as many intermediate colours they like in order to "blend" the colours, it isn't possible to make a completely smooth transition from each colour. Teachers will need to make sure student know this, and showing the digital HR diagram above will help that.
- The white dwarf stage is completely detached from the main sequence, so it isn't possible to make one, and to be honest it wouldn't be best to include them anyways. White dwarfs are made of degenerate matter and their physics is slightly different to regular stars. Adding the stage might confuse students.

Below is a table showing the stars used to scale the model, their radii and how it should translate to stitch number. You are more than welcome to pick other stars to customise your model, but you will have to adjust the pattern.

| Name | Class | Radius | Stitches | Colour |
|---|---|---|---|---|
| Betelgeuse | SGB | 764 | 8499 (Too large to crochet) | |
| Rigel | SGB | 80 | 889 (Too large to crochet) | |
| Polaris | SGB | 40 | 444 (Too large to crochet) | |
| Aldebaran | RGB | 45 | 500 (cap at 50) | |
| BI 253 | O | 13.9 | 154 | |
| Orionis | B | 7.5 | 83 | |
| Vega | A | 2.5 | 27 | |
| Procyon | F | 2 | 22 | |
| Sun | G | 1 | 11 | |
| | K | | | |
| AB Doradus C | M | 0.9 | 10 (baseline) | |

## Pattern Instructions

The rows with a * star before them have a size corresponding to a star, these are the rows where you may want to embellish with a line at the end. If you do want to do so, it may be best to add a stitch marker on these rows to avoid all the counting at the end!

**The chain does not count as the first stitch in this pattern**, so please remember to not skip the first stitch!

## Red

Form a magic loop and create 6 sc in the loop, slip stitch into the first sc (6)

**Round 1**: Chain 1, make 1 sc in each stitch, slip stitch into the first sc (6)

**Round 2**: Chain 1, make 1 sc in each stitch, slip stitch into the first sc (6)

**Round 3**: Chain 1, *2sc in first stitch, 1 sc in each of next 2 sts* repeat one more time, slip stitch into the first sc (8)

**Round 4**: Chain 1, make 1 sc in each stitch, slip stitch into the first sc (8)

**Round 5**: Chain 1, make 1 sc in each stitch, slip stitch into the first sc (8)

**Round 6**: Chain 1, 1 sc in next 5 sts, 2sc in next stitch, sc to end, slip stitch into the first sc (9)

**Round 7**: Chain 1, make 1 sc in each stitch, slip stitch into the first sc (9)

***Round 8**: Chain 1, 1 sc in next 2 sts, 2sc in next stitch, sc to end, slip stitch into the first sc (10) (AB Doradus C Radius)

Fasten off and cut your yarn, switch to **orange** yarn and start in any stitch.

## Orange

**Round 9-14**: Chain 1, make 1 sc in each stitch, slip stitch into the first sc (10)

**Round 15**: Chain 1, 1 sc in next 4 sts, 2sc in next stitch, sc to end, slip stitch into the first sc (11)

Fasten off and cut your yarn, switch to **yellow** yarn and start in any stitch.

## Yellow

***Round 16**: Chain 1, make 1 sc in each stitch, slip stitch into the first sc (11) (Sun's Radius)

**Round 17**: Chain 1, 1 sc in each of next 3 sts, 2sc in each of next 2 sts, sc to end, slip stitch into the first sc (13)

**Round 18**: Chain 1, 1 sc in each of next 4 sts, 2sc in each of next 2 sts, 1 sc in each of next 4 sts, 2sc, sc to end, slip stitch into the first sc (16)

**Round 19**: Chain 1, 1 sc in each of next 5 sts, 2sc in each of next 2 sts, sc to end, slip stitch into the first sc (18)

**Round 20**: Chain 1, Sc, 2sc, 1 sc in each of next 2 sts, chain 6, skip 6 stitches, 1 sc in each of next 2 sts, *2sc, sc, * repeat between * * two more times, slip stitch into the first sc (22)

***Round 21**: Chain 1, make 1 sc in each stitch, slip stitch into the first sc (22) (Procyon Radius)

This should form a hole in which the Red Giant Branch (RGB) can be made into. **Stuff the branch up to the beginning of the hole**, as we will now work in the hole. Once the RGB is complete, we will return to the main sequence bit.

Fasten off and cut your yarn but keep the **yellow** as we will be using it again in this section.

# Red Giant Branch

## Yellow

**Round 1**: Chain 1 into the right-most sc from round 19 (this should be the bottom right "corner" of the hole), Using your crochet hook, make 6 sc in each of the unused sts from round 19, sc into the side of the stitch between the previous st and chain, 1 sc in each of 6 chains, 1sc in side of chain stitch and first stitch of round, slip stitch into the first sc (14)

**Round 2**: Chain 1, 1sc, *2sc, 2sc * repeat between * * to end of round, slip stitch into the first sc (21)

**Round 3:** Chain 1, 1sc in each stitch, slip stitch into the first sc (21)

**Round 4:** Chain 1, 1 sc in each stitch until 2 sts before the "top" of the branch (highest point), 2sc in each of next 4 sts, sc until the end, slip stitch into the first sc (25)

**Round 5:** Chain 1, 1 sc in each stitch, slip stitch into the first sc (25)

**Round 6**: Chain 1, sc until 2 sts before top of branch, 2sc in each of next 5 sts, sc until the end, slip stitch into the first sc (30)

Fasten off and cut your yarn, switch to **orange** yarn and start in any stitch.

## Orange

**Round 7**: Chain 1, 1 sc in each stitch, slip stitch into the first sc (30)

**Round 8**: Chain 1, 1 sc in each of next 14 sts, 2 sc in next st, 1sc in next 4sts, 2sc, 1 sc in next 4 sts, 2sc, sc to end, slip stitch into the first sc (33)

**Round 9:** Chain 1, 1 sc in each stitch, slip stitch into the first sc (33)

**Round 10:** Chain 1, Increase 7 sts evenly through round, slip stitch into the first sc (40)

**Round 11:** Chain 1, 1 sc in each stitch, slip stitch into the first sc (40)

Fasten off and cut your yarn, switch to **red** yarn and start in any stitch.

## Red

**Round 12**: Chain 1, *sc2tog, 1 sc in each of next 4 sts,* repeat 3 more times, sc2tog, 1sc in each of next 5sts, sc2tog, 1sc in each of next 5sts, sc2tog, 1sc in each of next 6 sts, slip stitch into the first sc (34)

**Round 13**: Chain 1, *sc2tog, 1 sc in each of next 3 sts,* repeat 3 more times, sc2tog, 1sc in each of next 4sts, sc2tog, 1sc in each of next 4sts, sc2tog, 1sc in each of next 5 sts, slip stitch into the first sc (28)

**Round 14**: Chain 1, *sc2tog, 1 sc in each of next 2 sts,* repeat 3 more times, sc2tog, 1sc in each of next 3sts, sc2tog, 1sc in each of next 3sts, sc2tog, 1sc in each of next 4sts, slip stitch into the first sc (22)

Begin stuffing the RGB at this point.

**Round 15**: Chain 1, sc2tog, 1sc, sc2tog, 1 sc in each of next 3 sts, sc2tog, 1sc, sc2tog, 1 sc in each of next 2 sts, sc2tog, 1sc, sc2tog, 1 sc in each of next 2 sts, slip stitch into the first sc (16)

**Round 16**: Chain 1, *sc2tog, 1sc* repeat 4 more times, sc2tog twice, slip stitch into the first sc (10)

**Round 17**: Chain 1, make 5 sc2tog, slip stitch into the first sc (5)

Cut a long tail and pull the yarn through all 5 sts on hook to close the sts into a circle. For security, pull the tail through a second time and weave in the end.

The RGB can be stuffed from the MS part.

## Return to Main Sequence

Switch to white yarn and start in any stitch.

### White

For the next 5 rounds, make 1 increase in each round. Space them randomly so that increases are evenly spread.

***Round 22-26:** Chain 1, 1 2sc increase in round, slip stitch into the first sc (27 at the end of round 26) (Vega's radius on round 26)

Fasten off and cut your yarn, switch to light blue yarn and start in any stitch.

### Light Blue

For the next 15 rounds, make 2 increases in each round, spaced evenly and trying not to stack increases on top of each other.

**Round 27-41:** Chain 1, make 2 2sc increases in round, slip stitch into the first sc (57 at the end of round 41)

Fasten off and cut your yarn, switch to **dark blue** yarn and start in any stitch.

## Dark Blue

For the next 5 rounds, increase 4 sts evenly per round, taking care not to stack too many stitches (although it will be unavoidable for some stitches)

**Round 42-46:** Chain 1, make 4 2sc increases in round, slip stitch into the first sc (77 sts at the end of round 46)

For the next 9 rounds, increase 6 sts evenly per round.

***Round 47-55:** Chain 1, make 6 2sc increases in round, slip stitch into the first sc (131 at the end of round 55) (Orionis radius on round 47)

Fasten off and cut your yarn, switch to **purple** yarn and start in any stitch.

## Purple

For the next 3 rounds, increase 6 sts evenly per round.

**Round 56-58:** Chain 1, make 6 2sc increases in round, slip stitch into the first sc (149 sts at the end of round 55)

**Round 59:** Chain 1, make 5 2sc increases in round, slip stitch into the first sc (154 sts) (BI 253)

**Round 60-61:** Chain 1, make 1sc in each stitch, slip stitch into the first sc (154 sts)

Begin stuffing up the model until dark blue.

**Do not** cut the yarn as we will be using it again in this section.

## Decrease/End of Main Sequence

Continue using **purple:**

**Round 62:** Chain 1, *make 1 sc2tog, make 1 sc in each of next 8 sts, make 1 sc2tog in next stitch, make 1 sc in each of next 7 sts* repeat 7 more times for a total of 16 decreases, 1sc in next 2 stitches and slip stitch into the first sc (138 sts)

**Round 63:** Chain 1, *make 1 sc2tog, make 1 sc in each of next 7 sts, make 1 sc2tog in next stitch, make 1 sc in each of next 6 sts* repeat 7 more times, 1sc in next 2 stitches and slip stitch into the first sc (122 sts)

**Round 64:** Chain 1, *make 1 sc2tog, make 1 sc in each of next 6 sts, make 1 sc2tog in next stitch, make 1 sc in each of next 5 sts* repeat 7 more times, 1sc in next 2 stitches and slip stitch into the first sc (106 sts)

**Round 65:** Chain 1, *make 1 sc2tog, make 1 sc in each of next 5 sts, make 1 sc2tog in next stitch, make 1 sc in each of next 4 sts* repeat 7 more times, 1sc in next 2 stitches and slip stitch into the first sc (90 sts)

The next set of rounds will make 8 decreases in each round.

**Round 66:** Chain 1, *make 1 sc2tog, 1 sc in next 9 sts* repeat 7 more times, 1 sc in next 2 stitches, slip stitch into first stitch (82)

**Round 67:** Chain 1, *make 1 sc2tog, 1 sc in next 8 sts* repeat 7 more times, 1 sc in next 2 stitches, slip stitch into first stitch (74)

**Round 68:** Chain 1, *make 1 sc2tog, 1 sc in next 7 sts* repeat 7 more times, 1 sc in next 2 stitches, slip stitch into first stitch (66)

**Round 69:** Chain 1, *make 1 sc2tog, 1 sc in next 6 sts* repeat 7 more times, 1 sc in next 2 stitches, slip stitch into first stitch (58)

**Round 70:** Chain 1, *make 1 sc2tog, 1 sc in next 5 sts* repeat 7 more times, 1 sc in next 2 stitches, slip stitch into first stitch (50)

Add the final bit of stuffing if needed!

**Round 71:** Chain 1, *make 1 sc2tog, 1 sc in next 4 sts* repeat 7 more times, 1 sc in next 2 stitches, slip stitch into first stitch (42)

**Round 72:** Chain 1, *make 1 sc2tog, 1 sc in next 3 sts* repeat 7 more times, 1 sc in next 2 stitches, slip stitch into first stitch (34)

**Round 73:** Chain 1, *make 1 sc2tog, 1 sc in next 2 sts* repeat 7 more times, 1 sc in next 2 stitches, slip stitch into first stitch (26)

**Round 74:** Chain 1, *make 1 sc2tog, 1 sc in next st* repeat 7 more times, 1 sc in next 2 stitches, slip stitch into first stitch (18)

**Round 75:** Chain 1, make 1 sc2tog in each of next 4 sts, 1sc, 1sc2tog in each of next 4 sts, 1sc, slip stitch into first stitch (10)

**Round 76 (final round yay!):** Chain 1, make 5 sc2tog, fasten off and cut a long tail, pull the tail through all 5 sc2tog to close the work, for extra security pull the tail through a second time and weave in ends.

## Embellishment

While it is best to use black yarn, you can use any yarn that contrasts with the colours well. If you find that you chain stitches very tightly, increase your hook size.

Begin with a slip knot on your hook, push your needle into the side of any stitch on your row, wrap the yarn and pull a loop through, slip this loop and you have one chain embellishment! Repeat this for every stitch across the row and fasten off once you have all stitches. I knotted both tails together to join the chain line, then sewed in the ends using a tapestry needle.



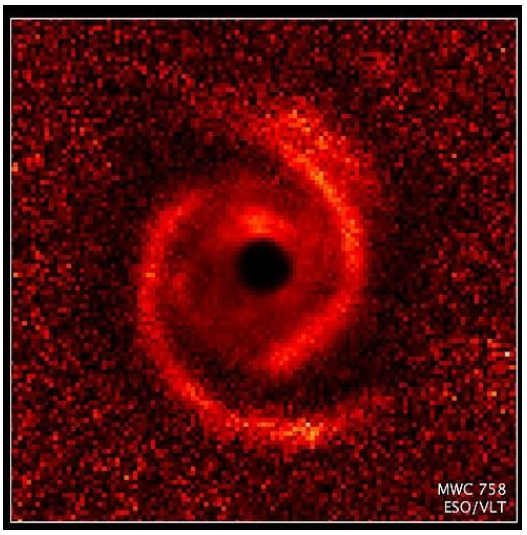
# Protoplanetary Disks

## What is a Protoplanetary Disk?

Protoplanetary disks are disks of dusty and gas orbiting a new star. The disk is the stage before planets and asteroids, where dust and gas hasn't clumped together to form anything yet. Our solar system would have begun with a large protoplanetary disk, in which Earth and the other planets would have formed from.

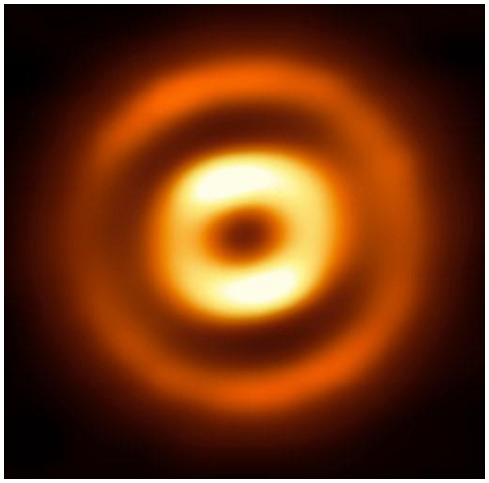
Research on the disk has grown exponentially over the past few decades, yet to this day how the disk turns into planets is still greatly unknown. While there are many protoplanetary disks in the observable universe that astronomers can study, the transition from disk to planet takes millions of years and thus we're unable to easily figure out how planets form. Planets often end up at vastly different locations as to where they formed, so there may also be a migration period that astronomers are also unsure of.

### Early stage and Late stage Protoplanetary Disk




Early in the solar system's life, the disk would be somewhat unstable and essentially "finding its foot". At this stage, no planets would be forming yet, but the disk would likely have a loose and flocculent spiral pattern. At a later stage, the disk should reach stability and planets may start forming and become prominent parts of the disk.

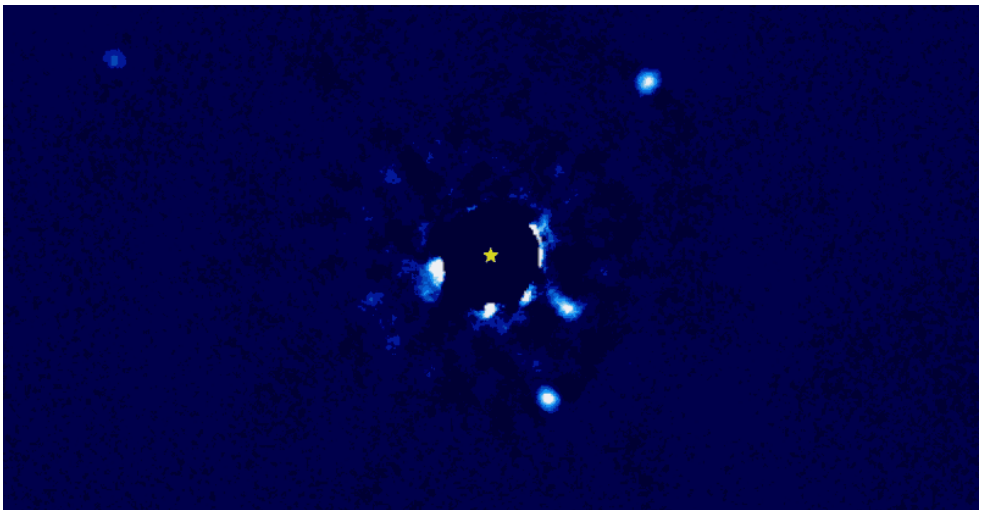
On the right is a young disk, MWC 758. The picture shows a  protoplanetary disk around the young star. The disk has two spiral arms that extend over 10 billion miles from the star. Credit to ESA/HUBBLE/ESO for the image.



A slightly older protoplanetary disk would be HD 169142. This image shows the dusty disc encircling the young, isolated star HD 169142. The vivid rings are thick bands of dust, separated by deep gaps. These deep gaps were likely carved out by giant protoplanets.

The image credit goes to ALMA (ESO/NAOJ/NRAO)/ Fedele et al.

Finally after millions of years, the disk is all swept up and a solar system is made. HR 8799 has eliminated the disk entirely, and is now a fully formed solar system. This is one of the extremely rare times exoplanets have been directly observed!



Credit to Jason Wang (Caltech)/Christian Marois (NRC Herzberg)

## Pattern Instructions

Below are two patterns, one for the early stage disk and the other for the late stage disk. Both start off with the same pattern for the central star, but after that the patterns differ. The early stage spiral disk is much more tedious than the late stage, so many images will be provided to help with crochet. The late stage disk requires a small amount of stuffing.

The late stage disk pattern is not yet ready! This booklet will be updated when it is!

**The chain does not count as the first stitch in this pattern**, so please remember to not skip the first stitch!

### Central Star

You're welcome to use any colour as set out in the 3D Hertzsprung-Russell Diagram, the model in this booklet is **yellow** to match the Sun.

Make a magic loop and create 6 sc in the loop.

**Round 1:** Chain 1, make 2sc in each sc, slip stitch into the first sc (12sts)

**Round 2:** Chain 1, *make 2sc in the first sc, 1sc in the next stitch * repeat 5 more times and slip into the first stitch (18 sts)

**Round 3:** Chain 1, *make 2sc in the first stitch, 1 sc in the next 2 stitches * repeat  more times and slip into the first stitch (24 sts)

**Round 4 & 5**: Chain 1, Make 1sc in each stitch and slip into the first stitch (24sts)

**Round 6**: Chain 1, Make 1sc in the back loop of each stitch and slip into the first stitch (24sts) (this back loop row will leave the front loops open for making the disk)

**Round 7:** Chain 1, Make 1sc in each stitch and slip into the first stitch (24sts)

**Round 8:** Chain 1,  *make 1 sc2tog, then make 1 sc in each of the next 2 stitches* repeat 5 more times and slip into the first stitch (18 sts)

Begin stuffing the black hole at this point.

**Round 9:** Chain 1 *make 1 sc2tog, then make 1 sc in the next stitch * repeat 5 more times and slip into the first stitch (12 sts)

**Round 10:** Chain 1, make 6 sc2tog and slip into the first stitch, cut the yarn with a long tail and stitch the 6 sc2tog stitches closed together.

## The Early-Stage Planetary Disk

This part of the instructions will not be so formally written and more picture-based due to the fiddliness. We will be working in the back loop on the star, and be making 6 spirals at the same time

Select either 2, 3 or 6 colours for your disk (these numbers fit into 6 nicely), in the pictures **black, red** and **orange** were chosen. If 2 colours are picked, these colours will be repeated 3 times each in the pattern, so it may be best to make small balls of the colours from a large

store-bought ball. 3 colours require each colour to be used twice (in this case I used the outer end and the inner end of each ball).

Begin with colour 1 with a standing sc in any back loop of the star, make 1 sc in each of the next 2 back loops, then make a 2 hdc increase in the next stitch, leave the colour and switch to colour 2.

In the stitch next to the 2hdc increase, make a standing sc with colour 2, then make 1 sc in each of the next 2 back loops, then make a 2 hdc increase in the next stitch, leave the colour and switch to colour 3.

Repeat the 3sc and 2hdc increase pattern for colour 3, and switch to a new ball of colour 1. Repeat the 3 colour pattern on the other side. Do not slip into any stitches!
Continuing on, as this can become increasingly complicated we will grow the disk by making a few stitches in each colour and work our way around the disk bit by bit.

Begin with swirl 1 and make 3 hdc in each of the next 3 stitches (these will be the stitches from swirl 2), make 2 hdc in the next stitch and leave swirl 1 to repeat the same for swirl 2 and so on.

Above shows where to put the stitches. Not slipping and chaining is what makes the continuous spiral.

Swirl 1 complete.

Swirl 2 complete.

All of the swirls complete.

After working through all swirls you should have returned back to swirl 1. Make 1 hdc in each of the 3 stitches in swirl 2, then make 2hdc in the next stitch and leave swirl 1 to repeat for the rest of the swirls (essentially, repeat the previous “round”).

Swirl 1 complete.

All of the swirls complete.

For the next part, continue on with  swirl 1 with 1 hdc in each of the next 4 stitches, then a 2hdc in the next stitch. Repeat this for all swirls 6 more times.

All swirls completed once.

All the swirls complete for the seventh time. Note how if you trace one of the colours it ends up right back to where it started.

After the repeats, the colours should have roughly returned to their original point. We will now make shorter stitches to “circle-ify” the disk and finish it off.

Continue in any swirl, make 1 hdc in each of the next 2 stitches, make 1sc in each of the next 4 stitches, make a slip stitch in the next 2 stitches and fasten off on the final slip. Weave in the end. Repeat this for the rest of the swirls.

Image of the final few stitches.

Below is the final model. Congratulate yourself for working 6 tails at a time!

## Customising your disk

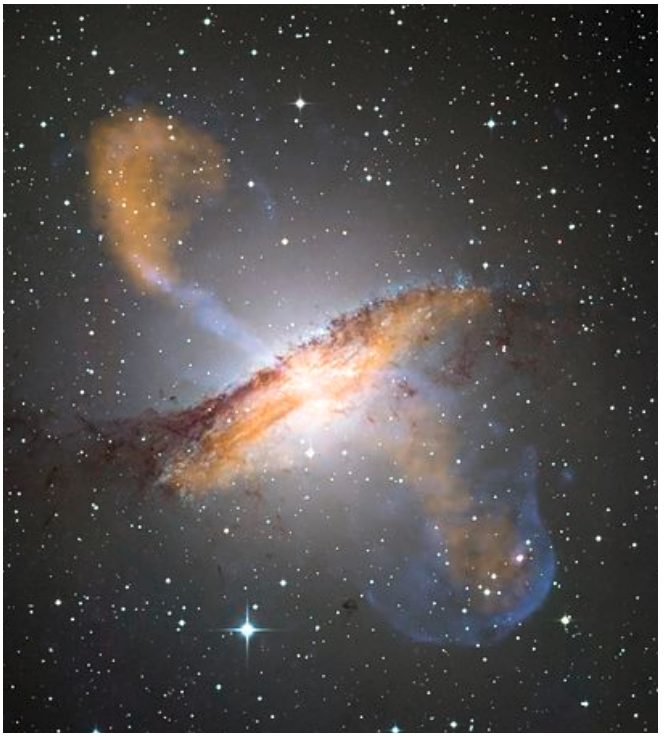
While working your pattern, you might want to add little “proto-planets”. To do this, you will need to switch colours in one swirl to white. In the final pull through in your hdc, pull a

white loop instead of the swirl colour. Chain 1 and make 3dc, take your swirl colour and pull a loop through the white loop on your hook and through the chain 1. This gathers the white dc into a popcorn stitch while also changing the yarn back to the swirl. Cut the white yarn and weave in the ends well.

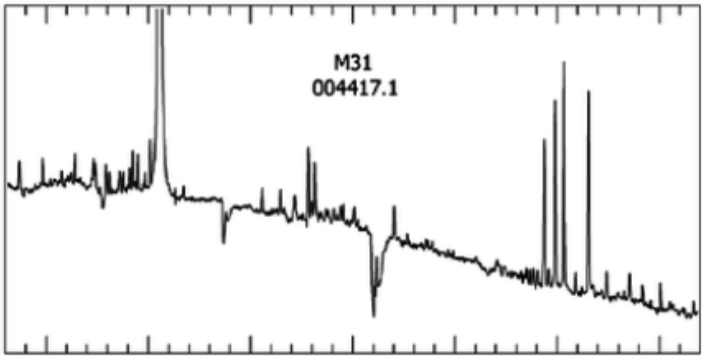
Another embellishment is to make the disk more 3D. To do this, insert some craft wire into the outer stitches of the disk like below. Disks tend to be more wobbly than purely flat, so you can bend the wire into a more wavy shape!

## Active Galactic Nuclei & Seyfert Galaxies

Active Galactic Nuclei (AGN) are the centres of the most luminous galaxies in the universe. They produce extremely high luminosities, and they're usually brighter than the stars in the galaxy, such as in quasars. This meant that the first AGN were mistaken for stars by early astronomers in the 50s and 60s. The reason we could tell they weren't stars is because when we factor in distance, their magnitudes brighter than the brightest stars we can see, and their spectra which tells us what element and how much is in the galaxy is different to stars.

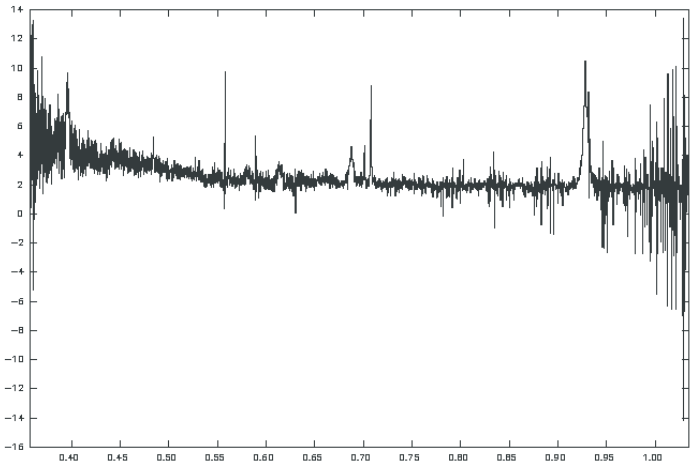


Credit: ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)




Here's a star from the Andromeda Galaxy, almost all the lines are sharp and long, and the baseline (continuum) peaks and slopes down. This tells us it's a black body and must be a star.

Credit to R.M Humphreys et al.

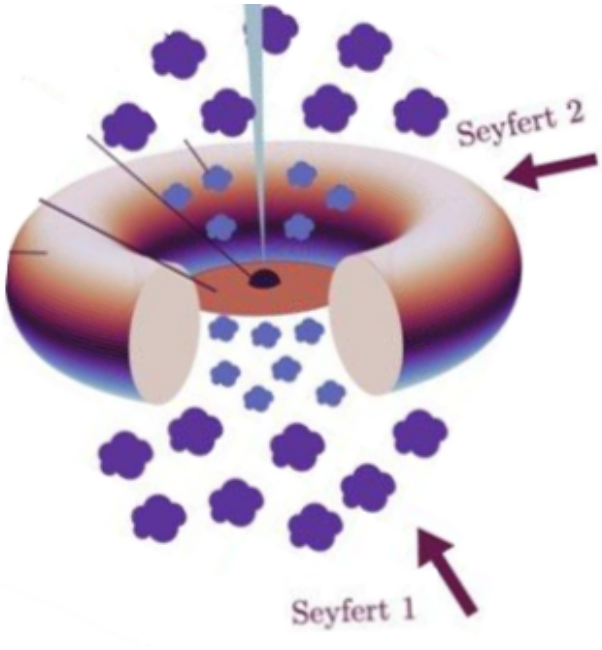


This is an AGN spectra that I made from XMM Slew data. It doesn't have a baseline black body shape, and it has broad shallow lines because of moving gas. It also has a lot of noise on the far left and far right that comes from a lot of different sources that aren't just stars.

My own spectra of a Seyfert 1. Data from XMM Slew & supervisor R. Starling.

Most AGN are classified as quasars and Seyferts. Quasars have a luminosity that overpower the stars in the galaxy, whereas with Seyferts the stars are usually somewhat visible. The difference between the two types is more historical than science-based, and it's not really important what we call them.

**What Makes up an AGN?**




Credit: Emma Alexander

AGN have 4 important features that can change a lot about their spectra: The supermassive black hole in the centre (that's the black dot), the broad line region (BLR, lilac smaller clouds near black hole), narrow line region (NLR, dark purple larger clouds), and a dusty torus (the doughnut).

The black hole fuels the activity and produces the extreme brightness by accreting (eating) matter. It will sometimes also produce high energy jets as well. Even the biggest supermassive black holes in the universe don't actually eat much matter, sometimes less than the mass of the sun is enough to fuel a quasar!

The broad line region (BLR) is made of really high energy fast moving gas. It's very close to the black hole, so it feels the gravitational effects the most! It's called the BLR because it is responsible for the broad lines in the spectra. It broadens the lines because the gas is moving so fast that it can make its own little redshifts and blueshifts which stretches the lines out.
The NLR is much further out and doesn't move as fast as the BLR. Lines aren't as broad, but they will never be perfectly sharp either.

The dusty torus shrouds the broad line region and black hole, and is made of clumpy dust and gas. This means that at an edge-view of the galaxy, we won't be able to see the broad line region and hence we don't see broad lines in its spectra, only narrow (the arrow labelled Seyfert 2 on the diagram). However, if we have a more direct view of the galaxy, we can see the broad line region and hence broad lines. This would be a Seyfert 1 and is marked with the arrow on the diagram. This is one of the key theories that unite both types of Seyfert Galaxies and has heavy implications on the early universe, when galaxies started forming!

## What the pattern is showing

This pattern will be a somewhat not-to-scale representation of the broad and narrow line region around a black hole and enveloped in a torus. The torus will be big enough to obscure the broad line region at near side view angles, but small enough to be crocheted in a suitable time.

## Pattern Instructions

Begin with **black** yarn for the black hole.

**The chain does not count as the first stitch in this pattern**, so please remember to not skip the first stitch!

## The Black Hole

Make a magic ring and chain 1. This does not count as a stitch. Make 6sc in the magic ring and slip stitch into the first sc.

**Round 1**: Chain 1, make 2sc in each sc, slip stitch into the first sc (12sts)

**Round 2:** Chain 1, *make 2sc in the back loop of the first sc, 1sc in the back loop of the next stitch * repeat 5 more times and slip into the first stitch (18 sts)

**Round 3:** Chain 1: Make 1sc in each stitch and slip into the first stitch (18sts)

**Round 4:** Chain 1: Make 1sc in the back loop of each stitch and slip into the first stitch (18sts)

**Round 5:** Chain 1: Make 1sc in each stitch and slip into the first stitch (18sts)

Begin stuffing the black hole at this point.

**Round 6:** Chain 1, *Make a sc2tog in the first stitch, 1sc in the next stitch*  repeat 5 more times and slip into the first stitch (12 sts)

**Round 7:** Chain 1, make 6 sc2tog and slip into the first stitch, cut the yarn with a long tail and stitch the 6 sc2tog stitches closed together.

Switch to your chosen BLR colour (**yellow** in the image)

## The Broad Line and Narrow Line Region

To make the BLR and NLR we will be working in the 12 front loops leftover from round 2.

**BLR Round:** Begin with a standing sc in any of the front loops, * make 1 sc in the next 2 stitches, 2sc in the next stitch, 1sc in next stitch * repeat 2 more times, slip into the first stitch, cut tail and fasten off. (15sts)

Switch to your chosen NLR colour (**orange** in the image)

**NLR Round 1:**  Begin with a standing sc in any of the stitches, * make 1 sc in the next 2 stitches, 2sc in the next stitch, 1sc in next stitch * repeat 2 more times, make 1 sc in the next 2 stitches, 2sc in the next stitch, slip into the first stitch (19sts)

**NLR Round 2:** Chain 1, *Make 1sc in each of next 5 stitches, 2sc in next stitch * repeat 2 more times, 1 sc in next stitch, slip nto the first stitch (22 sts)

**NLR Round 3:** Chain 1, *make 1 sc in each of next 4 sts, 2sc in next stitch, make 1 sc in next 5 stitches, 2sc in next stitch * repeat one more time and sip into the first stitch, fasten off and weave in ends (26 sts)

## Dusty Torus

Begin with your Torus colour (**white** in the image)

To make the torus we will be working in the 18 front loops made in round 5 (this should be at the equator of the black hole).

**Torus round 1**: Make a standing sc in any of the front loops, make 1 sc in each of the front loops and slip stitch into the first sc made (18 sts)

**Torus round 2**: Chain 1, *make 2sc in first stitch, make 1 sc in each of next 2 stitches * repeat 5 more times, slip stitch into the first sc (24 sts)

**Torus round 3**: Chain 1, *make 2sc in first stitch, make 1 sc in each of next 3 stitches * repeat 5 more times, slip stitch into the first sc (30 sts)

**Torus round 4:** Chain 1, *make 2sc in first stitch, make 1 sc in each of next 4 stitches * repeat 5 more times, slip stitch into the first sc (36 sts)

**Torus round 5:** Chain 1, *make 2sc in first stitch, make 1 sc in each of next 5 stitches * repeat 5 more times, slip stitch into the first sc (42 sts)

**Torus round 6:** Chain 1, *make 2sc in first stitch, make 1 sc in each of next 6 stitches * repeat 5 more times, slip stitch into the first sc (48 sts)

**Torus round 7:** Chain 1, *make 2sc in first stitch, make 1 sc in each of next 7 stitches * repeat 5 more times, slip stitch into the first sc (54 sts)

**Torus round 8:** Chain 1, *make 2sc in first stitch, make 1 sc in each of next 8 stitches * repeat 5 more times, slip stitch into the first sc (60 sts)

**Torus round 9**: Chain 1, make 1 sc in each stitch, slip into the first sc ( 60sts)

**Torus round 10-14:** Repeat Torus round 9 (60 sts)

**Torus round 15:** Chain 1, *make 1 sc2tog in first stitch, make 1 sc in each of next 8 stitches * repeat 5 more times, slip stitch into the first sc (54 sts)

**Torus round 16:** Chain 1, *make 1 sc2tog in first stitch, make 1 sc in each of next 7 stitches * repeat 5 more times, slip stitch into the first sc (48 sts)

**Torus round 17:** Chain 1, *make 1 sc2tog in first stitch, make 1 sc in each of next 6 stitches * repeat 5 more times, slip stitch into the first sc (42sts)

**Torus round 18:** Chain 1, *make 1 sc2tog in first stitch, make 1 sc in each of next 5 stitches * repeat 5 more times, slip stitch into the first sc (36 sts)

**Torus round 19:** Chain 1, *make 1 sc2tog in first stitch, make 1 sc in each of next 4 stitches * repeat 5 more times, slip stitch into the first sc (30 sts)

**Torus round 20:** Chain 1, *make 1 sc2tog in first stitch, make 1 sc in each of next 3 stitches * repeat 5 more times, slip stitch into the first sc (24 sts)

**Torus round 21:** Chain 1, *make 1 sc2tog in first stitch, make 1 sc in each of next 2 stitches * repeat 5 more times, slip stitch into the first sc (18 sts)

Fasten off with a very long tail, as this will be used to sew the torus shut. Read this paragraph in full before sewing, as it will explain how to stuff and sew the torus together. Using a tapestry needle, sew round 17 to round 1 by running the needle through a sc "top" from round 17, then run the needle through the back " bump" of the corresponding round 1 stitch. The easiest way to stuff the torus as you go is to sew about 5 stitches, then stuff a little bit of the torus and repeat until the torus was nearly sewn. At the halfway point, you can use a finger to move around the stuffing if needed.

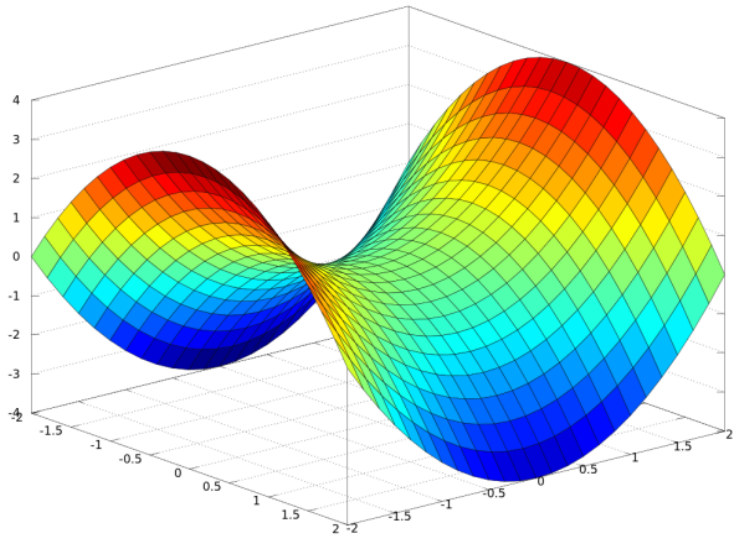
Weave in the end and marvel at your mini AGN!

Moving the AGN model from side-view to bird’s eye changes the visibility of the Broad Line Region, and hence changes the spectrum of the AGN!

## Cosmological Geometry

At some point in a cosmology student's life, they will come across the Friedmann-Lemaitre-Robertson-Walker FLRW metric which describes the shape of plain empty space as the universe expands/contracts in time and come to find the curvature constant k. The k constant tells us what kind of geometry describes the universe, with 3 possible types:

- When k > 0, the curvature is spherical and closed. Space expands until a critical point, then contracts. This kind of universe has a lot of matter in it, so that eventually gravity overcomes expansion and causes contraction.
- When k = 0, the curvature is flat. This is a critical universe, a perfect balance of expansion and gravity. The universe will slowly (but never) stop expanding.
- When k < 0, the curvature is hyperbolic and open. This universe has little matter in it, not enough to balance expansion, instead this universe will continue to expand forever. Below is a graphical and real life example of hyperbolic geometry. It looks like a pringle, but it can also look like coral.



Coral that's experienced bleaching from human impact. Credit: William West/AFP/Getty Images.

Flat and spherical geometry are simple enough to understand for college level students, but pupils will likely have never heard of hyperbolic geometry. Modelling such a surface is extremely difficult, but crochet can do this very simply, with a lot of personal customization available! Crochet can also easily make hyperbolic surfaces with either a Cartesian frame of view, or spherical polar frame of view.

Crochet is holdable, and students can open out parts of the surface to get a feel for what is going on with the surface. Also, the stitches are countable and can be used to explain the shape better (this will be elaborated on in the pattern itself). And, lines can be sewn onto the model to show things like divergence by following the stitches.

## The Patterns

Outlined are 3 example patterns for each surface. For spherical and hyperbolic geometry, there Is actually no set pattern for a sphere or hyperbole, but a set of maths that allow you to create your own pattern. The maths will be outlined, with an example pattern for those who would rather not look at a calculator.

**The chain does not count as the first stitch in this pattern**, so please remember to not skip the first stitch!

## Spherical

With the spherical universe, each row has the same amount of increases (it is 6 in our case), they just spread out with each row, and then swap the increases for decreases to make the other half of the sphere.

**Beginning:** Create six single crochet stitches in a magic loop and join with a slip stitch. (6)

**Row 1:** Chain 1, make 2 sc in each stitch, join with a slip stitch. (12)

**Row 2:** Chain 1, *2sc in one stitch, 1 sc in next stitch * repeat from * to last stitch. Join with a slip stitch. (18)

**Row 3:** Chain 1, *2sc in one stitch, sc in each of next 2 stitches * repeat from * to last stitch. Join with a slip stitch. (24)

**Row 4:** Chain 1, *2sc in one stitch, sc in each of next 3 stitches * repeat from * to last stitch. Join with a slip stitch. (30)

Customise the size of the sphere by increasing the number of rounds according to the pattern. For example round 5 will have a repeat *2sc in one stitch, sc in each of next 4

stitches* etc. Add one more sc to each repeat. This will need to be mirrored in the decrease portion.

**Rows 7:** Chain 1, make 1sc in each stitch, join with a slip stitch. (30)

Repeat row 7 two more times.

**Row 8:** Chain 1, *sc2tog in one stitch, sc in each of next 3 stitches * repeat from * to last stitch. Join with a slip stitch. (24)

**Row 9:** Chain 1, *sc2tog in one stitch, sc in each of next 2 stitches * repeat from * to last stitch. Join with a slip stitch. (18)

You might want to start stuffing your universe at this point.

**Row 10:** Chain 1, *sc2tog in one stitch, sc in each of next stitch * repeat from * to last stitch. Join with a slip stitch. (12)

**Row 11:** Chain 1, *sc2tog * repeat from * to last stitch. Join with a slip stitch. (6)

Fasten off and sew together all the stitches. Neaten the tail by pulling it into the sphere and chopping off the excess.

Ways to customise: As noted in the pattern , you can increase the size by adding rounds. You can also add rounds in between where you do no increases/decreases, creating a more conic shape.

## Flat

There are 2 ways to create a flat surface. One way works the piece flat & square with rows, and the other works in rounds and makes a circle.

### Square Cartesian surface (the easier method)

**Beginning:** Chain any amount of stitches.

**Row 1:** Chain 1, make 1 sc in the 2nd chain from the hook and sc to the end of the row. Alternatively, chain 2 and dc in the 3rd chain from the hook and dc to the end of the row. Turn your work.

Repeat row 1 until your universe is big enough. Cut the yarn and pull the tail though the last stitch.

## Circular Polar Method

Make a magic loop and chain 1, make 6sc in the loop.
**Round 1:** Chain 1, Make 2sc in each stitch, slip into the first stitch (6)
**Round 2:** Chain 1, *make 2sc in the first stitch, make 1 sc in the next stitch * repeat 5 more times, slip into the first stitch (12)
**Round 3:** Chain 1, *make 2sc in the first stitch, make 2 sc in the next stitch * repeat 5 more times, slip into the first stitch (18)
**Round 4:** Chain 1, *make 2sc in the first stitch, make 3 sc in the next stitch * repeat 5 more times, slip into the first stitch (24)

Continue in this pattern, making a 2sc increase, then 1sc in the next x stitches, where x is the round number minus one e.g round 5 has 1sc in each of the next 4 stitches.

Continue this until you have a universe large enough to your liking!

# Hyperbolic

The hyperbolic universe is very customizable. In the spherical universe, we increase each row with the same amount, but in the hyperbolic universe we increase the amount of increases.

All you need to do is start with an increase rate. In the pattern below, I will make 3 dc for every 2 dc in the previous row (i.e I am increasing my stitches by 1.5 x in each row.) To do this, my pattern repeat will be *2dc, dc*

Experiment with your own rate of increase, but I recommend that you don't increase more than 2dc per dc. 1 stitch becomes 2 and then 4, then in 6 rows time you have 128 stitches. That's not fun, especially since we're starting with 12 stitches, not 1!

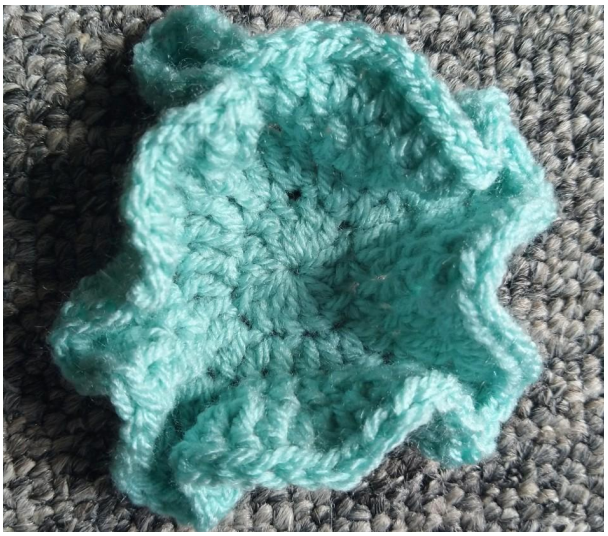
**Beginning:** Make 12 dc in a magic loop (12)

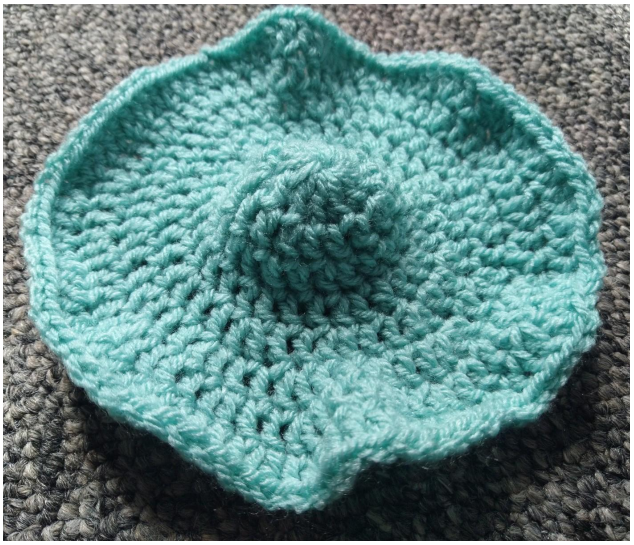
**Row 1:** Chain 2 *make 2dc in the next stitch, make 1 dc in next stitch * join with a slip stitch. (18)

Sometimes the pattern repeat won't always complete at the end of the row depending on your increase rate. Don't worry, that's perfectly fine!

Repeat row 2 until the universe is big enough, or you're too tired.

The above has an increase rate of 1.5 (2dc in 1 stitch, 1dc in th next), but below is an example where every stitch is doubled (2dc in every stitch), and one where there's an increase rate of 1.3 (2dc in 1 stitch, 1 dc in next 2 stitches).





## Black Hole Spacetime Geometry

Note: Solar Mass = the mass of the Sun (2 x 10^30 kg). 2 solar masses means twice as heavy as the Sun.

### What is a Black Hole?

Black holes are the final stage of large stars in the current universe. These large stars (usually over 2-3 Solar masses) will stop being able to fuel themselves with nuclear fusion, and their gravity will cause them to collapse to the point where not even electrons and neutrons can hold up the star. This is why stellar sized black holes are sometimes called collapsars.

There are also supermassive black holes (SMBH) that exist in almost all large galaxies, but their origin is still unknown. These kinds of black holes are thousands to billions of solar masses, and ones that are accreting matter and producing high luminosities are called active galactic nuclei (AGN). No scientist yet knows how supermassive black holes came to be, and if they are just stellar black holes that have grown, how those stellar black holes managed to grow so quickly.

This orange fuzzy galaxy is so dense and has such a big black hole that it's bending the galaxy behind it's light into a ring! This is called an Einstein ring. Credit: ESA/Hubble.

Black holes are so dense and have such high mass & gravity that spacetime warps around them and distorts light. This is really useful for measuring mass, because more mass means more distortion. Black holes bend space close to them into a specific shape, called a Flamm's paraboloid, and those that rotate have an extra component called frame-dragging.

## Types of Black Hole

Because light cannot escape a black hole once it passes the event horizon, we can only see 3 properties: mass (we can see that from the distortion), electric charge (not-so-easy to tell), and angular momentum (spinning). Every black hole needs mass, but they might have a combination or none of the other two properties as well.

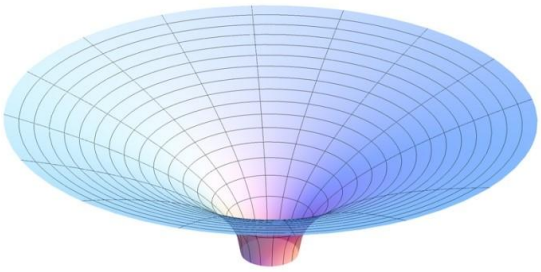
This means there are 4 types of black hole: Schwarzschild (mass only), Reissner-Nordström (mass + charge), Kerr (mass + rotation), and Kerr-Newman (all three).

What's interesting is that charges around a black hole like to neutralize, negative charges attract positive and balance. So in general, black hole can be considered neutral/chargeless, and for the purpose of the crochet models we're about to make, we don't need to consider Reissner-Nordström and Kerr-Newman physics!

Think of Schwarzschild black holes as plain artificial vanilla ice cream, and Kerr black holes as proper Madagasan vanilla. Kerr-Newman could perhaps be Madagascan vanilla with sprinkles and sauce: nice but not necessary to enjoy the taste of the ice cream!

Schwarzschild black holes bend spacetime around them into a Flamm's paraboloid, which is described by the formula below and looks like this:

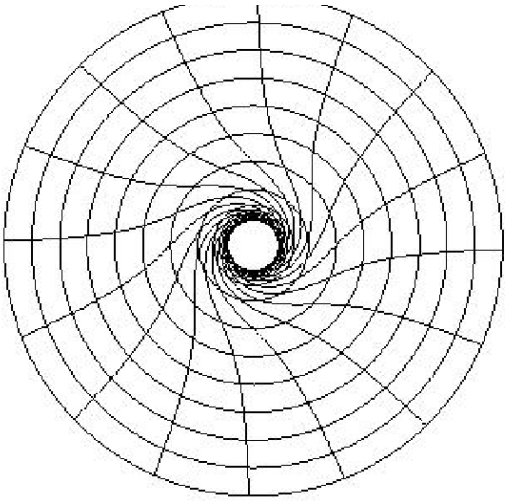
$$w = 2\sqrt{r_s\,(r - r_s)}.$$



Credit: Allen MC

What's interesting is that the paraboloid doesn't start from one tiny point like regular shapes, but it starts with a small ring at the bottom. The explanation for this is in the formula above. The start of the paraboloid is when w = 0, and to get that you need r to equal the $r_s$ term. This is the radius of the black hole(the event horizon), and that makes sense because this spacetime distortion must start right outside the black hole.

When the black hole rotates, however, the paraboloid distorts a bit more! The curvature of spacetime is somewhat distorted with the rotation of the black hole, as though it were spinning with the black hole! This is called frame dragging, and that alone is extremely difficult to visualise. P.C Van der Wijk in their thesis graphs out a visualisation for this frame dragging:



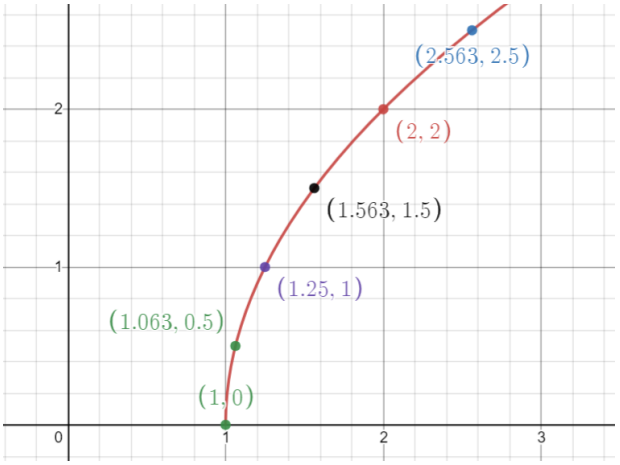
And as you might be able to see, this looks like a bird's-eye-view of the Flamm's paraboloid, but with a twist (no pun intended)!

## What the Pattern is Showing

The crochet models consist of two Flamm's paraboloids, one being normal (Schwarzschild), and one having frame-dragging included (Kerr). The simpler normal paraboloid isn't all that useful on its own, but there are very few visual representations of frame-dragging.Together, these could be very useful in showing what frame dragging looks like and how a particle might move around a black hole.

### Creating the Pattern:

I graphed the formula for Flamm's paraboloid and found points with equally spaced apart y values (so y=0, 0.5, 1, 1.5 etc) and noted their corresponding x coordinates. That way, I can make each y value be 1 round of crochet, and the x values will tell me how much I need to increase. Basically, when the x coordinate increases, the circumference of the crochet needs to increase by the same amount, which is useful for crochet as we're just making a lot of circumferences stacked on top of each other.




| Round | X-value | Stitches needed |
|---|---|---|
| 1 | 1 | 10 |
| 2 | 1.063 | 11 |
| 3 | 1.25 | 13 |
| 4 | 1.563 | 16 |
| 5 | 2 | 20 |
| 6 | 2.563 | 26 |
| 7 | 3.25 | 33 |
| 8 | 4.062 | 41 |
| 9 | 5 | 50 |
| 10 | 6.063 | 61 |

For example in the graph above, I start with 1 stitch in the 0th row (which is technically the first row), then in the next row that 1 stitch increases to 1.063 stitches. In order to make a tube, I need to start with many stitches, so for example if I cast on 10 stitches, then in the next round I will need 10.63 ~ 11 stitches, and this is how I can increase in accuracy.

The table has the number of stitches set out for a paraboloid that starts with 10 stitches:

## The Pattern

I used half double crochet (hdc), but this pattern is customisable.

### Black Hole Base

**Foundation Round:** chain 10 and made a slip stitch into the first chain to join in the round.

**Round 1**: Chain 2, make 1 hdc in each chain, slip into the first hdc. (10)

**Round 2:** Chain 2, make 1 hdc in each of next 4 chains, make 2 hdc in next stitch, hdc in each of the rest of the stitches, slip into the first hdc. (11)

**Round 3**: Chain 2, make 2 hdc in next stitch, hdc in each of next 5 stitches, make 2 hdc in next stitch, hdc in each of the rest of the stitches, slip into the first hdc. (13)

**Round 4:** Chain 2, * make 2hdc in next stitch, hdc in each of next 3 stitches, * repeat 2 more times, hdc, slip into the first hdc. (16)

From now on make increases evenly spaced throughout the round.

**Round 5:** Chain 2, hdc in each stitch while making a total of 4 increases, slip into the first hdc. (20)

**Round 6:** Chain 2, hdc in each stitch while making a total of 6 increases, slip into the first hdc. (26)

**Round 7:** Chain 2, hdc in each stitch while making a total of 7 increases, slip into the first hdc. (33)

**Round 8:** Chain 2, hdc in each stitch while making a total of 8 increases, slip into the first hdc. (41)

**Round 9:** Chain 2, hdc in each stitch while making a total of 9 increases, slip into the first hdc. (50)

**Round 10:** Chain 2, hdc in each stitch while making a total of 11 increases, slip into the first hdc. (61)

You can keep on going as long as you want, but I stopped here. Below is the finished piece:


## Sewing Instructions

The gravitational lines can be backstitched, but you could also use a crochet slip stitch along the top of the fabric. To back stitch, first thread a tapestry needle with a long tail of yarn of a contrasting colour for the best definition.

Make a knot in the back of one stitch in the last row, the end can be woven in later. Poke the needle through the stitch to bring the yarn to the front.  To start the back stitch, bring the needle back down the fabric In the stitch from the next row, this creates the first stitch. Then repeat the step but instead bring the needle up from the underside from the next row. Take the needle and bring it back down through the previous row, then bring the needle up from the next row. This forms the repeat of the backstitch. Continue backstitching in either one of the two shapes below.


Use a long piece of yarn so you can work all the lines in one go without working multiple ends. Between each line just simply thread the yarn discreetly through the back of the stitches until you get to where you need to be. Your backstitches will not always be even because some stitches will be worked diagonally, so do not worry! To keep things fairly even, your backstitches should only be made one per row I.e. each stitch will only be roughly 1hdc stitch long.

## Schwarzschild Black Hole

Sew in a straight line from the edge to the centre. Start at the bottom of a stitch and work vertically upwards, adding no horizontal component. Make at least 3 lines to see the pattern best.



## Kerr Black hole

Start by stitching a wide spiral by making your stitches very slightly moving diagonally. For my model, each back stitch started from the bottom left of a crochet stitch, and finished at the top middle. After working past the third row, increase the spirality and diagonality of the stitches so that all back stitches go from the bottom left to the top right of each crochet stitch. This should make them look more tightly coiled up when all the lines are complete.





## Further Crochet Projects

I hope these projects are fun and perhaps helpful in your learning! Future projects will include a late stage protoplanetary disk, an image of the first prototype will be shown below. This will be a slightly more time-consuming model because of the stuffing.

Other projects include early cosmology inflation fields. These delve way more into the abstract and is probably the most higher-level topic of them all. And also a more complete "build your own AGN" style project that includes a BLR & NLR on both sides and relativistic jets with Fanaroff-Riley FR1/FR2 (central/limb brightening) colour changes.

## Acknowledgements

Some of these patterns were heavily inspired by the crochet works of Dr Liz George. Her Centaurus A model and images of her other toys are fantastic and I highly recommend you visit her Ravelry.

The stellar radii values were taken from the NASA SIMBAD database, specifically AB Doradus C, Procyon A, Vega, Upsilon Orionis and BI 253.

Protoplanetary disk images have corresponding credits next to them, with information on the disks taken from Introduction to Mineralogy and Petrology by S.K. Haldar and Josip Tišljar (2014).

AGN images have respective credits next to them, with information taken from Introduction to Active Galactic Nuclei by B.M Peterson (1997).

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The frame-dragging diagram and all information is credited to the amazing thesis written by P.C van der Wijk.

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