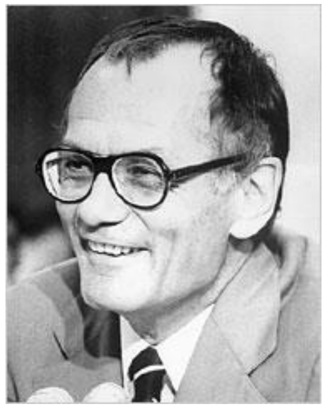

Fig. 11.1. Dr. Robert Jastrow

Chapter 11. Weather Prediction

Dr. Jastrow was brilliant. If he had not been eclipsed by Carl Sagan, he would have been famous. Jastrow's television series on space science in the 1960s was widely viewed and his book[1] based on those programs, *Red Giants and White Dwarfs*, was a popular masterpiece on the evolution of stars, planets and life. However, in the 1970s Jastrow's appearances as Johnny Carson's guest on the *Tonight* show were largely displaced by Carl Sagan.

Jastrow's management style at GISS was imperial, at least during the period I knew him, which began in early 1967. Joop Hovenier, during his first visit to GISS, remarked: "It's incredible, that man rules by fear!" That was after Joop sat in Jastrow's outer office waiting to see him and observed the interactions between Dr. Jastrow and the people working for him.

Yet Jastrow's intellect and drive were attractive. He brought in topflight scientists. Jastrow was good at stirring the intellectual pot and focusing discussion on specific objectives. The topic of prime interest to him in the early and middle 1970s was how weather forecasts might be improved with the help of satellite observations.

I attended several of the 'weather' meetings. Participants included meteorologists Jule Charney of MIT and Vern Suomi of the University of Wisconsin. Charney was a pioneer in the use of fundamental equations to describe the structure and motions of Earth's atmosphere. Suomi, known as the father of satellite meteorology, had the second science instrument on a United States satellite, after Van Allen's Geiger counter. Suomi was the first to employ the spin-scan imaging technique[2] that we later adopted for our Pioneer Venus imaging polarimeter.

The most useful information for improving forecasts would be measurements of wind speeds at different altitudes in the atmosphere. That would allow us to see how the atmosphere was circulating, how the weather systems were moving. Unfortunately, it is not easy to see the wind.

Suomi's idea was to infer wind speeds by observing the movement of clouds. The utility of this data was limited by the fact that clouds do not occur in all regions of the globe at a given time, upper clouds shield lower clouds from view, and cloud altitudes are not known accurately.

Charney had a different idea, which was complementary to Suomi's, because Charney's method would work best in cloud-free regions. Charney's proposal was based on use of atmospheric temperature profiles measured by satellites. Temperature profiles are obtained by measuring the infrared radiation emerging at the top of the atmosphere at several different wavelengths.

Radiation in the center of a strong CO_2 absorption band arises from high in the atmosphere, while radiation from successively weaker bands arises from deeper and deeper in the atmosphere. Radiation at wavelengths with no gas absorption arises from the ground. The magnitude of the radiation provides a measure of the temperature at each of these levels.

Charney's proposal was to insert observed temperatures into a weather model, providing correct initial conditions for model simulations of future weather. Correct temperatures would also help the model calculate realistic winds, which are driven by temperature and pressure gradients.

A problem with Charney's plan was that satellite temperature measurements were not 'correct' – they included substantial errors, as the satellite technology was still being developed. Accuracy could be improved, however, by comparing satellite data with radiosonde (balloon) data at a number of stations around the world. The satellite algorithms could thus be 'trained' at a few locations by 'truth' at the few radiosonde stations to give better satellite results all around the world. Of course, radiosondes had their own errors, so it was a lot of work to get the best result.

Intellectual fervor generated competition, as is common in science. One of Dr. Jastrow's secretaries once ran down to my office concerned that Charney was having a heart attack. Charney was at a desk in Jastrow's outer office, on the phone with Jastrow, who was working at home, as was often the case. Jule Charney was a warm, congenial person, but in this instance he was coughing and highly agitated. He loudly accused Jastrow of stealing his ideas in a paper on satellite-aided forecasting that Jastrow had submitted for publication.

Those difficulties were soon smoothed out. However, the task of putting these ideas into practice, of testing them with real global observations, was a huge job, one that would take many years. It was not a job that Charney or Jastrow would want to manage on a day-to-day basis.

Milt Halem was Jastrow's lieutenant managing the weather prediction project. The project was challenging because of the still primitive status of computers, weather models, satellite instruments and satellite data analyses. The project had to deal with all of these facets, with a team that included about 60 people on the support services contractor staff.

Milt was a tough taskmaster, yet it was hard not to like him. With his roundish, dimpled face and curly hair, he was like a big teddy bear. Milt was loyal to Jastrow, accepting ambitious targets and working at them harder than anyone. He was an optimist and sometimes jovial, so underlings did not mind working for him, even though he was demanding.

The atmosphere could be tense when Dr. Jastrow got involved. In one exchange, Dr. Jastrow berated a young scientist for being slow and punctuated his demand by firing a blackboard erasure that hit the retreating scientist squarely in the buttocks. Dr. Jastrow frequently played handball in the Columbia University gym – that practice must have been good for his aim.

Development of a weather model became the principal activity at GISS. Charney recommended that GISS start with the UCLA two-layer weather model developed by Akio Arakawa and Yale Mintz. Arakawa was a mathematical wizard who devised a stable numerical scheme to solve the equations of atmospheric motion in a way that properly conserved mass, energy and momentum, while including essential physics such as solar heating of the atmosphere and ground.

Arakawa was a genius, but his English was almost unintelligible. When he gave a talk at a GISS conference, the stenographer wrote hama-hama-hama – she could not understand a word he was saying. The main function of Prof. Mintz seemed to be to translate and interpret Arakawa.

The UCLA model had to be modified for our intended application. The atmosphere needed to be divided into many layers, so that the model could usefully incorporate satellite measurements of the atmosphere's vertical temperature profile.

The model also should incorporate accurate physics for the heating of the atmosphere and surface. Ozone and water vapor, for example, absorb sunlight. Ozone absorption heats Earth's stratosphere, at heights 15-30 miles, while water vapor absorbs sunlight in the troposphere, the lowest several miles of the atmosphere.

I was the obvious person at GISS to provide this physics, because the calculations needed to include the effect of light scattering by clouds and aerosols. Surely, that was part of the reason that Dr. Jastrow sought a promotion for me just 18 months after I was hired.

The promotion package was in my personnel folder, which was given to me on the day that I left NASA in 2013. The folder contained records of my hiring, promotions, security clearances, and so on, including a 1 October 1973 memo from Dr. Jastrow to George Pieper, Director of Space Sciences recommending that I be promoted to GS-14 (government's equivalent of associate professor) from the GS-13 level.

I describe this promotion procedure as an example of how a still young NASA worked. Later I will contrast this with NASA's civil service system as the agency aged. The sclerosis that developed extends throughout our government. It is fixable, but it is not being addressed.

There is another reason to be explicit. I will contrast evaluation at this point with that later in my career, after I began to question NASA management priorities and programs. Issues will include not only efficient use of taxpayer dollars, but acquisition of information critical for understanding the future of our planet and the well-being of young people.

A lot had changed in 18 months! Now Jastrow said of me "…along with Drs. Thaddeus and Halem he has shouldered more management responsibilities than any other civil service scientist at GISS…". Also, thanks to our Pioneer Venus and other planetary funding, my group had become one of the main reasons for NASA support of the Goddard Institute.

Jastrow's memo requesting my promotion included laudatory evaluations, e.g., from Richard Goody of Harvard ("Hansen's work is highly reliable and very solid. When he does something, people believe it, which is not true of a lot of others. He is about the best man in the field in the world, now that van de Hulst is not actively publishing.") Jastrow noted that "Goody's closing endorsement of Hansen as the best in the international community is especially significant because Goody is the most critical and caustic scientific personality in this field."

Inflation of evaluations is standard practice in promotion packages. In reality, Hovenier was the best-grounded young researcher in polarized light scattering, we would both soon be eclipsed by Michael Mishchenko, and none of us could hold a candle to van de Hulst.

Light scattering in Planetary Atmospheres, the paper I was working on at that time, turned out to be my last paper in atmospheric radiation. I did not intend to abandon the field – I thought that I would work together with Andy Lacis on atmospheric radiation. But I was pulled by a siren in a different direction. It was an unfamiliar, dangerous route. We could easily crash on the rocks, and it might be difficult to turn back, if we set sail in that direction.

Chapter 12. The Ozone Connection

Paul Crutzen and Harold Johnston pointed out that supersonic aircraft proposed in the early 1970s might reduce stratospheric ozone via chemical reactions initiated by nitrogen oxides in aircraft exhaust.[3] Ozone absorbs ultraviolet sunlight, preventing the most energetic ultraviolet rays from reaching the ground, where they would be damaging to humans and other life.

Other objections to supersonic transports (SSTs) included their noise pollution. Battles ensued in the U.S. Congress. Planetary scientists were involved, because atmospheric chemistry studies of other planets provided a broad understanding and a powerful atmospheric simulation capability.

Detailed modeling[4] confirmed the concerns of Crutzen and Johnston, although effects on ozone were found to be less than initially feared. The U.S. decision against commercial development of SSTs was based mainly on concerns about their commercial viability.

Mario Molina and Sherry Rowland,[5] however, soon identified a serious threat to ozone: chlorine (Cl) released in the stratosphere by photodissociation of chlorofluorocarbons (CFCs). Chemical reaction of Cl with ozone (O_3) results in conversion of ozone to oxygen (O_2), thus causing a depletion of stratospheric ozone.[6] CFCs were a serious threat to the ozone layer.

The scientific community did an exceptional job of guiding rigorous assessment of the CFC threat and communicating the implications to the public and policymakers. The resulting Montreal Protocol and CFC phasedown did not pop out of the blue. The research community deserves much of the credit for these successes.

I describe the science community's guidance regarding ozone depletion because later I must contrast it with much less successful scientific guidance in the case of climate change. Blame for failure of governments to stem climate change cannot be placed solely on politicians and the fossil fuel industry. We scientists bear a large portion of the responsibility.

The planetary science community included researchers who were among the most expert on Earth's stratosphere, including Tom Donahue and Don Hunten, who co-chaired Pioneer Venus meetings. They and a small group of the leading researchers exerted extraordinary influence in shaping the research program that was needed to provide good policy advice to governments.

An initial issue was the choice of government agency responsible for the ozone science program. Scientists should let policymakers decide that, right? Not according to Hunten and Donahue!

That issue came up earlier: who should manage investigation of the SST effect on stratospheric ozone? The Department of Transportation (DOT) was entrusted with that research program. Was the fox being asked to guard the hen house? Like putting the Energy Department in charge of a CO_2 and climate program? That management debacle will be discussed later!

Hunten, Donahue, and others argued forcefully that an independent science agency should be given responsibility for stratospheric research. An ongoing research program could provide knowledge useful to assess the SST and CFC issues, and the knowledge could help head off other potential problems before they became major headaches.

These scientists preferred that the stratospheric science program be located in NASA. Some official accounts credit agency bureaucrats with affecting the congressional decision, but that is not how it worked according to Rasool, who was then chief scientist at NASA Headquarters.

Congress people and their staffers like to speak directly to scientists who know what they are talking about. The advice they got was to assign the program to NASA. In June 1975, Congress passed legislation directing NASA to conduct a comprehensive stratospheric research program.

I was fortunate to attend some of the early meetings of the research leaders. Like in my first physics courses, I sat in the back row and tried to be inconspicuous. Most issues concerned atmospheric chemistry. Discussion was collegial. Mike McElroy was in his element in the repartee, once quipping "age before beauty" as he deferred to Tom Donahue.

A big workshop was held in Washington, DC, giving all scientists a chance to offer suggestions about the nature of the budding program. I summoned up the courage to proffer comments about the need to monitor stratospheric aerosols, because aerosols affect atmospheric chemistry, and also a comment about the value of comparing Earth's atmosphere with that of other planets.

Paul Crutzen, then manager of atmospheric chemistry at NCAR, nearly bit my head off. Perhaps he thought that I was suggesting that stratospheric research funding be used to support research on other planets. I was not about to talk back to a legend, even if I had the debating tools, which I did not. I was still smarting at Crutzen's sharp rebuke on the way home.

The issue relates to a basic problem affecting science. Disciplines tend to become specialized, each in its own silo. One way to combat isolation is housing different disciplines in proximity. Solution to specialization, however, also requires housing multiple disciplines in the same brain.

Planetary science is a small field. Planetary scientists are often renegades, living in physics or astronomy departments. That is an advantage. It helps planetary scientists acquire a broad interdisciplinary background, which is useful for Earth studies.

I decided to write a proposal to try to get our group into stratospheric research. Discussions had focused on chemistry, for which we had no background. But there were other interesting issues. What about the effect of ozone change on climate? That is largely a radiation problem.

Atmospheric dynamics, as well as chemistry, would be needed for that problem, because atmospheric motions affect how ozone-depleted air gets spread around the planet. So we would need a three-dimensional model to study the problem. However, if we look at Earth from a planetary perspective, at the large scales of Earth's atmospheric circulation, it seemed to me that it may be sufficient for the model to have coarse spatial resolution.

Andy Lacis and I had already worked on the GISS weather model for a few years. We were co-authors on a paper[7] describing the weather model and we wrote our own paper[8] describing an efficient way to calculate atmospheric radiation in global models. The weather model was cumbersome and slow, because its spatial resolution was the finest that our computer could handle. The decade-old GISS computer, which was still the IBM 360/95 purchased in 1967, allowed resolution only as fine as about 400 km (about 250 miles). In other words, the model divided the world up into boxes with the area of the state of Georgia.

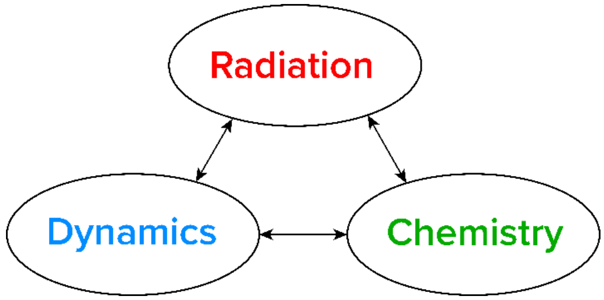

Fig. 12.1. Chart used for 1975 research proposal to Rasool and Hunten.

Georgia-size resolution was too coarse to make a good weather model, but too fine for what I had in mind. My suspicion was that ozone depletion might be usefully addressed with a still coarser resolution. The model's computing time is inversely proportional to the cube of the model resolution.[9] So if the resolution is made 800 km, instead of 400 km, the computing is $2 \times 2 \times 2 = 8$ times faster. With a resolution of 1200 km, the model is 27 times faster.

My opinion on this would not mean much. The issue concerns atmospheric dynamics. What scale of atmospheric motion is essential for global transport of atmospheric ozone? Fortunately, Prof. Peter Stone of MIT, a world expert in atmospheric dynamics, agreed that coarse resolution may be sufficient for many purposes. And he was eager to work with us in developing a model.

Ichtiaque Rasool was the point person at NASA Headquarters for stratospheric research, when Congress assigned the program to NASA in 1975. Given that the science was focused on atmospheric chemistry, how could I persuade Rasool that we had something to offer?

Ozone change would not only alter the amount of UV radiation reaching Earth's surface, it would also affect Earth's energy balance. A planet's energy balance is determined by radiation: the amount of solar radiation absorbed by the planet and the amount of heat radiation emitted to space. So I could argue that it was important to do the radiation calculations accurately.

Ozone's effect on atmospheric radiation is complicated. Ozone (O_3) is a triatomic molecule, like CO_2 and H_2O, so it absorbs infrared (heat) radiation. In other words, it is a greenhouse gas.

However, ozone also absorbs sunlight, mainly in the stratosphere. Most sunlight reaches Earth's surface, causing a maximum temperature at the ground. Temperature decreases with height in the lower atmosphere, the troposphere, up to a height of about 10 miles (about 15 km). Above that height, because of ozone absorption, temperature increases to a maximum at the top of the stratosphere, at a height of about 30 miles (about 50 km).

So if humans alter ozone, they can change the entire temperature structure of the atmosphere. This was an argument why NASA needed radiation experts in its stratospheric research program.

I flew to Washington on the 6 AM Shuttle, earlier than necessary for a late morning meeting with Rasool, but I wanted to be sure to avoid air traffic delays that frequently affected LaGuardia and National airports. The extra time was useful. I thought of a good introductory chart.

Those were days when scientists carried felt-tipped pens and transparent plastic pages on which we could write, making 'viewgraphs' that could be projected on a screen or wall. At the airport I drew a diagram, three ovals labeled Radiation, Dynamics and Chemistry, connected by arrows.

The chart got me in trouble, because I put Radiation at the top. Rasool was amused by this. He called in a Headquarters colleague who was passing the conference room. "Look, this is interesting, Jim thinks that radiation is the most important part of the ozone problem!"

Rasool was trying to have a good time in the dull Headquarters job that he had got himself into. But he would not make a funding decision without expert advice. He got Don Hunten on the speaker-phone. I felt tense as I haltingly tried to explain what I was proposing. Hunten, who tended to be caustic and critical, was silent for a long time.

"Sounds like a good plan," a gruff voice came from the box on Rasool's desk. Whew! Hunten elaborated. He said that there was only enough money the first year for high priority tasks, such as measurements of chemical reaction rates. However, funding in the next year was likely.

Hunten provided a strong piece of advice; we should seek a talented young chemist for our team. He said Mike McElroy had cornered the market, he had most of the best post-docs.

When I got back to New York, I called McElroy. He expressed interest in collaboration and said that we might have a chance with one of his best proteges, Yuk Ling Yung, who was about ready to strike out on his own. We agreed that Yung should visit GISS and give a seminar.

Yuk Ling Yung's enthusiasm was infectious. He paced back and forth in front of the blackboard. Phrases and sentences came out in chunks, staccato, as he explained how and why atmospheric gases are changing. Yuk revered his mentor, describing McElroy's 'red book,' a review of the state of knowledge of atmospheric chemistry, as "the bible."

We needed to get moving, Yuk said. There was exciting research to do. The atmosphere of our home planet was changing. We better understand it, because there are likely to be consequences. A planet that is changing is the most interesting planet to investigate.

CO_2 was not the only greenhouse gas humans were changing. Veerabhadran Ramanathan had shown[10] that the greenhouse effect of human-made CFCs was significant. Surely other gases were also changing, even though measurements had not been made yet.

Hunten was right. Yung's expertise in chemistry complemented ours in radiation. We decided to work on a paper together. He would discuss what gases were likely to be changing, and we would calculate the potential greenhouse effect of each gas.

We soon focused on nitrous oxide (N_2O) and methane (CH_4), because we knew they had strong absorption bands that would make them effective greenhouse gases. Yuk argued that N_2O must be increasing because of increasing use of nitrogenous fertilizers, and CH_4 should also be increasing because of agricultural sources, landfills and leakage in fossil fuel mining.

The climate effect of N_2O and CH_4 was overlooked by the scientific community. The World Meteorological Organization (WMO) issued a major report[11] stating categorically that "minor constituents like N_2O, CH_4, etc. are present in such small concentration that their direct effects are negligible" and they "can have only an indirect effect on the energy budget of the planet (through participating in the photochemistry of ozone or the production of particulate matter)."

We were confident in our calculations and certain that the WMO report was wrong. Our paper[12] was the lead article in the 12 November 1976 issue of *Science*. The topic quickly grew in importance, when measurements of N_2O and CH_4 became available.

Earth, it became clear, was not only the most important planet, because it harbored life, but also the most interesting. My priorities changed rapidly. We needed a climate model to help understand changes occurring on Earth, but as yet we had no funding to build a model.

That's where Kiyoshi Kawabata came in. We hired Kiyoshi in 1973 to work on planetary research. Kiyoshi had worked with Prof. Ueno on radiation problems, and he happily jumped into calculations to investigate aerosols and clouds on Venus.

However, when I failed to get immediate funding for modeling, we needed a 'volunteer' to work on the weather model, so we could experiment with coarser resolutions. Kiyoshi was the willing victim. It took a few months, but he got the weather model to work with alternative resolutions. To our delight, 1000 kilometer resolution produced realistic atmospheric circulation. Of course, Akio Arakawa, architect of the UCLA weather model deserved credit for his design of the numerical schemes that conserved important physical quantities at all resolutions.

Successful simulation at a coarse resolution helped us write a good proposal. The coarse resolution model was fast enough that we could incorporate chemistry and accurate radiation physics into it. That allowed us to investigate problems including interactions among different parts of the climate system, as suggested by the diagram that I had shown in Rasool's office.

Yuk was the other critical element. We had potential to form a formidable, internationally recognized group. Yuk was ticketed to be a leader in atmospheric chemistry, Peter Stone was already an authority in dynamics, and we had in-house radiation expertise.

I presented the situation to Dr. Jastrow. He understood the potential. We had to offer Yuk a civil service staff position to attract him. Dr. Jastrow agreed to have dinner with Yuk and me, to help sell Yuk on the idea. On the day of our dinner, Dr. Jastrow played handball, but said that he would meet us at the restaurant, the Moon Palace, across Broadway from GISS.

It was awkward. Yuk and I sipped green tea, assuming that Dr. Jastrow was delayed. Finally, we realized that he was not going to show up. Yuk and I ate by ourselves. I suppose it was unlikely we could have captured Yuk anyhow, or at least not kept him for long. He accepted a tenure-track position at the California Institute of Technology the next year. So, we would collaborate with Yuk and with McElroy, but we did not have an in-house atmospheric chemist.

Nevertheless, the die had been cast. My priority became climate modeling. It would be a struggle to find support. NASA was not lavishing support on GISS the way they had in the early days of the space program, when Headquarters provided funding for a large number of international research leaders to work at GISS.

The stratospheric research program provided a modest amount of funding. My group's main support, however, was from the planetary program. The Pioneer Venus program was ramping up. We made frequent trips to California, where our polarimeter for the Pioneer Venus mission was being built. Larry Travis gradually took over most Pioneer Venus duties, but it was difficult to make much progress in climate modeling, given our small number of people, each with multiple obligations.

Just then, an explosion occurred. Sometimes, amidst falling debris and embers, new opportunities arise. So it was with the NASA weather and climate eruption.

[1] Jastrow, R., *Red Giants and White Dwarfs*, Warner Books, 275 pp., 1979. Red giants and white dwarfs refer to later phases in the life cycle of stars, including our Sun, that have an initial mass similar to that of the Sun.

[2] The easiest way to stabilize a spacecraft is to set it spinning. A simple telescope on a spinning spacecraft can acquire one line of data as the telescope's field of view scans across the planet. Successive scans as the spacecraft orbits the planet can build up an image of the planet.

[3] Crutzen, P.J.: The influence of nitrogen oxides on the atmospheric ozone content, Quart. J. Roy. Meteorol. Soc., 96, 320-325, 1970; Crutzen, P.J.: SST's – A threat to the Earth's ozone shield, Ambio, 1, 41-51, 1972. Johnston, H.: Reduction of stratospheric ozone by nitrogen oxide catalysis from supersonic transport exhaust, Science, 173, 517-522, 1971.

[4] McElroy, M.B., Wofsy, S.C., Penner, J.E. and McConnell, J.C.: Atmospheric ozone: possible impact of stratospheric aviation, J. Atmos. Sci., 31, 287-303, 1974.

[5] Molina, M.J. and Rowland, F.S.: Stratospheric sink for chlorofluoromethanes: chlorine atom catalyzed destruction of ozone, Nature, 249, 810-812, 1974.

[6] $CFCl_3$ and CF_2Cl_2, with trade names CFC-11 and CFC-12, popularly called Freons, are a product of Dupont Chemical (now Chemours). CFCs were used mainly in refrigeration and as propellants in spray cans, hair sprays and deodorants, for example.

[7] Somerville, R.S. et al., The GISS model of the global atmosphere, *J. Atmos. Sci.*, **31**, 84-117, 1974.

[8] Lacis, A.A. and J.E. Hansen, A parameterization for the absorption of solar radiation in the Earth's atmosphere, *J. Atmos. Sci.*, **31**, 118133, 1974.

[9] If the horizontal resolution increases by a factor of two, there are $2\times2 = 4$ boxes within the prior larger box. In addition the model's time step, which is proportional to the time required for the wind to blow across the box, must be decreased by the factor 2.

[10] Ramanathan, V., Greenhouse effect due to chlorofluorocarbons: climatic implications, Science, 190, 50-52, 1975.

[11] World Meteorological Org., The physical basis of climate and climate modeling, GARP Publ. Ser. No. 16, 1975.

[12] Wang, W.C., Y.L. Yung, A.A. Lacis, T. Mo and J.E. Hansen, Greenhouse effects due to man-made perturbations of trace gases, *Science*, **194**, 685-690, 1976.